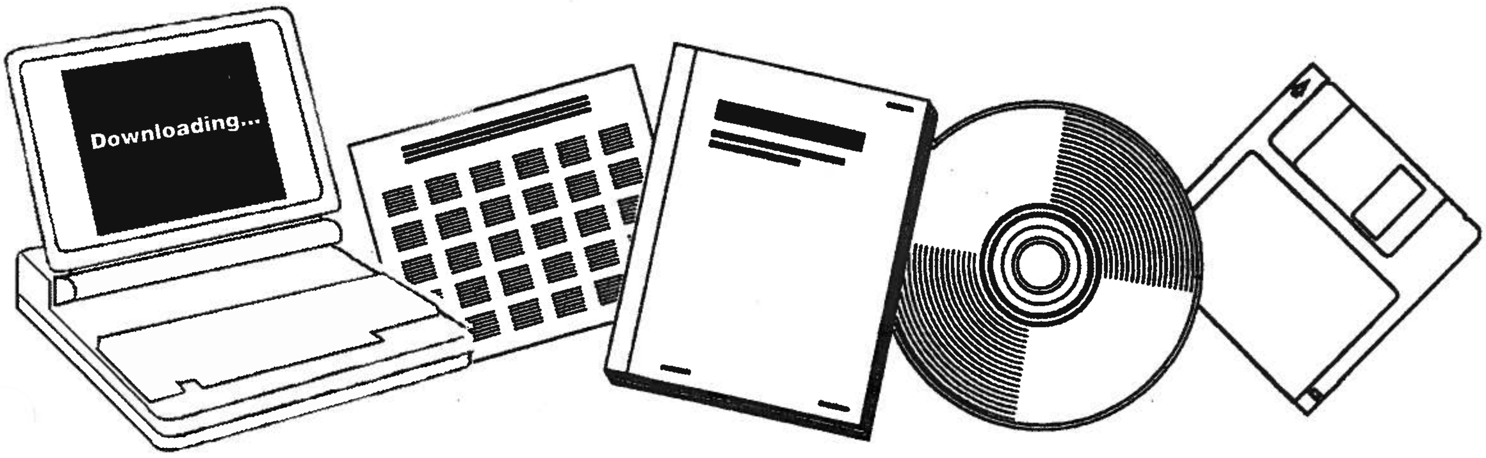
PB213201

ESCAPE WORTHINESS OF VEHICLES FOR OCCUPANCY SURVIVALS AND CRASHES. FIRST PART: RESEARCH PROGRAM

OKLAHOMA UNIV. RESEARCH INST., NORMAN

JUL 1972



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PB 213 201

ESCAPE WORTHINESS OF VEHICLES FOR OCCUPANCY SURVIVALS AND CRASHES

First Part: Research Program

University of Oklahoma
Research Institute
Norman, Oklahoma 73069

Contract No. FH-11-7512
July 1972
Final Report

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PREPARED FOR:
U.S. DEPARTMENT OF TRANSPORTATION
NATIONAL HIGHWAY TRAFFIC SAFETY ADMINISTRATION
WASHINGTON, D.C. 20590

604

TECHNICAL REPORT STANDARD TITLE PAGE

1. Report No. DOT/HS-800 736	2. Government Accession No.	3. Recipient's Catalog No. PB-213 201

4. Title and Subtitle
ESCAPE WORTHINESS OF VEHICLES FOR OCCUPANCY SURVIVALS AND CRASHES First Part: Research Program

5. Report Date
July 1972

6. Performing Organization Code

7. Author(s) C. M. Sliepcevich, W. D. Steen, J. L. Purswell, R. F. Krenek, J. R. Welker, T. D. Peace, R. E. Cullen, J. N. Ice, R. G. Rein, Jr.

8. Performing Organization Report No.

9. Performing Organization Name and Address
University of Oklahoma Research Institute
Norman, Oklahoma 73069

10. Work Unit No.

11. Contract or Grant No.
FH-11-7512

13. Type of Report and Period Covered
Final Report
6/1/70 to 7/31/72

12. Sponsoring Agency Name and Address
U.S. Department of Transportation
National Highway Traffic Safety Administration
Washington, DC 20519

14. Sponsoring Agency Code

15. Supplementary Notes
See also PB 198 772 and PB 198 773.

16. Abstract

This is a final report of the results of a multidisciplinary study of the factors involved in escape of occupants from crashed vehicle environments in which the vehicle is incapacitated on land, submerged in water, or involved in fire. This effort continues the studies initiated under NHSB Contract FH-11-7303, the final report for which is available from the National Technical Information Service. The present report consists of two parts in two volumes.

The report presents analyses of police accident reports, fire department run reports and other data on motor vehicle collision fires and submergences. Analytical modeling and other analytical techniques are provided for predicting escape times from passenger cars and buses, for predicting vehicle collision-submergence water-entry conditions and sinking times, and for estimating strength available for the operation of escape exits. Other techniques allow prediction of ignition times and burning rates of vehicle interior materials. A considerable amount of other data related to vehicle interior (enclosure) fire behavior and toxic product generation, flammable characteristics of various fabrics and interior materials, fuel modification, effectiveness of fire extinguishers, and fuel system design practices are also included. The report includes a selective bibliography (799 entries).

17. Key Words
Escape Worthiness
Flammability
Submergence
Toxicity
Math Model
Motor Vehicle Fire & Submergence Frequency
Fire Control
Human Strength
Fuel Modification

18. Distribution Statement
unlimited

Reproduced from best available copy.

19. Security Classif. (of this report) unclassified	20. Security Classif. (of this page) unclassified	21. No. of Pages ~~639~~ 604	22. Price $9.00

Form DOT F 1700.7 (8-69)

SUMMARY

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The FIRST PART summarizes the investigative efforts, results, and conclusions. As an essential step in the development of techniques for objectively quantifying the performance of motor vehicle characteristics related to escape worthiness, a considerable body of data has been generated. Essentially the human and vehicle parameters which exhibit a demonstrable effect on relative ease of egress in an emergency situation have been identified and, in many instances, quantified. The most significant achievement during the current contract has been the development of several analytical models which establish the deterministic relationships among easily measurable escape parameters.

A survey of almost 10,000 published documents has reaffirmed the original finding that the literature is inadequate for the purposes of defining minimum safe escape worthiness of motor vehicles. Based upon the literature survey and a special effort to find a source agency for the information, it must be concluded that even the incidence of fire and burn injury as compared to fatality cannot be established. The problem of toxicity of combustion products from burning motor vehicle materials and the more pressing problem of short-time human tolerance limits for certain toxic gases are not addressed in the literature and probably receive little research attention. Analysis of a large sample of accident reports and other data on fire and submergence collisions in Oklahoma and Kansas again confirms the earlier finding that fatal and injurious effects are more frequent than other studies have estimated.

A predictive model for escape time from passenger cars which is based upon a set of easily measured vehicle dimensions has been developed. The model is effective for a range of vehicle sizes, with varying numbers of escape exits, for varying passenger populations. Other predictive model techniques related to vehicle collision-submergences have been developed for obtaining deceleration forces, velocities, attitudes, and depths attained in the water entry process and for estimating vehicle floating times. Other techniques have

been developed for estimating escape times from buses for a variety of conditions. Additional studies provide data on the design of exits and on human strength available to operate exit mechanisms.

The flammability research program has developed a generalized correlation of the ignition data for all the motor vehicle interior materials tested. An equation predicts ignition time from absorbed irradiance, density, and thickness of the material. A more significant achievement is the development of the quantitative relationship between ignition characteristics and burning rates. Burning rate of materials in any burn rate test method can now be predicted from the ignition data, the weight of material per unit area, and an apparatus calibration factor. Interior fire tests in a large enclosure provided data on fire behavior, material weight loss, temperature rise, carbon monoxide and carbon dioxide production, oxygen depletion, and smoke density. The colorimetric tube method for analysis of other toxic gases appeared too insensitive in these tests. Additional studies involved a review of fuel modification and fuel system construction practices, a brief series of severe fire extinguisher effectiveness tests, and an analysis of fire department run reports for motor vehicle fires.

The SECOND PART presents the appendices for the FIRST PART. Included are a bibliography, representative collision-fire and collision-submergence in-depth investigations, computer program documentation for the water-entry programs, analysis techniques for water and air-leak rate, vehicle sinking times, and vehicle volume measurement, and a biomechanical analysis of strength available for operating escape exit mechanisms. Appendices related to flammability include material identification lists, ignition data for interior fabrics obtained from the Illinois Institute of Technology, tabulations of horizontal and angled burning rates of materials, and a tabulation of smoke generation in the vehicle interior (large enclosure) fire test.

ABSTRACT

This is a final report of the results of a multidisciplinary study of the factors involved in escape of occupants from crashed vehicle environments in which the vehicle is incapacitated on land, submerged in water, or involved in fire. This effort continues the studies initiated under NHSB Contract FH-11-7303, the final report for which is available from the National Technical Information Service (PB 198 772 and PB 198 773). The present report consists of two parts in two volumes.

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CHAPTER ONE

INTRODUCTION

Under the broad subject description ESCAPE WORTHINESS OF VEHICLES FOR OCCUPANCY SURVIVAL AND CRASHES, this report presents the results of multi-disciplinary studies of the problems related to the escape of occupants from crashed motor vehicles on land, entered in water, or involved in a fire. These studies are a continuation and expansion of pilot studies conducted earlier under NHSB Contract FH-11-7303 and published in December 1970 under the title "Escape Worthiness of Vehicles and Occupant Survival."

The present research program was divided into two functional parts: the collection of empirical data through analysis of police accident reports, newspaper clippings, death certificates, and fire department run reports and through limited in-depth investigations of a few specific accidents involving escape hazards or impediments; and an extensive experimental and test program related to vehicle materials, vehicle design, and human factors.

This chapter presents the general objectives of the program, a recapitulation of the contribution of escape worthiness to motor vehicle safety, an account of the major accomplishments of the contractural effort, and finally, a description of the format and organization of this final report on Contract FH-11-7512.

1.1 THE RESEARCH PROGRAM

This work consisted of a multi-disciplinary investigation to evaluate the escape worthiness of land vehicles as related to occupant crash survivability as a logical extension of the investigative effort initiated under an earlier contract, FH-11-7303. The ultimate objective was to develop supporting data on which safety performance standards could be based. The scope of the program was limited to the extent that the occupants, just prior to and/or after the crash or development of an adverse envelope, were neither entrapped by deformation of the vehicle nor injured to the point where they could not take immediate advantage of available escape routes such as doors, windows and hatches. These limitations thus imposed a set of "ideal conditions" for escape, and consequently, only <u>minimal</u> performance requirements for safe egress were generated.

These studies consisted of three essential parts:

1. Analysis of information resources to determine whether escape worthiness parameters could be identified.
2. Development of the techniques for assessing the extent to which vehicle design characteristics provide for safe and easy egress of the occupants from adverse environments.
3. Delineation of the allowable extent of hazards associated with the two adverse crash environments, fire and water.

In the sense that the overall product of the research was to seek data for elimination or reduction of hazards which impair escape, major emphasis was directed towards the identification of deficiencies in current design practices which can be alleviated or rectified by modifications in the vehicle via performance standards. Thus, the substance of the experimental studies was in devising and evaluating methodologies for measuring performance quantities.

The period of performance for the subject matter included in this report covers 25 months of effort between June 1, 1970 and July 31, 1972. Originally the work program was negotiated on the basis of a period of 15 months extending from June 1, 1970 through August 31, 1971 although only 31 percent of the requisite funding was allocated in June 1970. Nevertheless, the work schedule based on a fully-funded program was pursued. Another 36 percent of the funding was allocated in November 1970 to carry the program through June 30, 1971. At this point it became necessary to reprogram the entire work effort in order to conform to the 23 percent decrease in the rate of funding. In order to salvage as much of the scope and intent of the original contract as possible, the work schedule was revised on the assumption that the remainder of the funding, amounting to 33 percent, would become available in July 1971. Simultaneously, the termination date of the contract was extended from August 31, 1971 to June 30, 1972 in order to achieve maximum utilization of experienced project personnel on the experimental phases of this program. The third and final funding increment was authorized in July 1971. Subsequently in April 1972, an extension of one month, from June 30 to July 31, 1972, as the official termination date of the contract period without incremental funding, was granted to allow more time for preparation of the final report.

Although the uncertainty in the funding, which compelled several major revisions in the task schedule (including some shifts in emphasis, scope and intent) had, to some degree, an adverse impact on the performance, it is believed, nevertheless, that the final results embodied in this report are more useful--and in many respects exceed the original objectives--than what might have been anticipated for less volatile circumstances.

1.1.1 Statement of Work and Objectives

The major objective of this research program was to continue to develop information which could be utilized by the Government as a basis for establishing minimum performance standards for enhancing escape worthiness of vehicles, occupant survival, and fire prevention or protection.

The collective effort of the research program, when viewed in the context of the multi-year research and development plan evolved under the earlier NHSB Contract FH-11-7303, had five ultimate purposes:

1. To develop occupant survivability criteria for vehicles impaired by adverse environments, with particular emphasis on water and fire.
2. To generate data concerning passenger car configurations that affect occupant escape from or survival in water or fire environments.
3. To develop supporting data on which to base the issuance of safety performance standards for emergency exits on buses.
4. To develop an acceptable test methodology for identifying significant factors related to flammability of vehicle interior materials of construction.
5. To assess the feasibility of modifying vehicle fuels and/or providing fire extinguishers for reducing hazards to occupants and mitigating losses from property damage.

This report constitutes a codification of the accomplishments related to the objective and purposes since many of the intermediate results have been previously transmitted on a piecemeal basis in monthly and special reports to the contract technical manager and in oral briefings for NHTSA personnel in Washington, DC on February 17, 1971 and on January 18, 1972. The final results of the major efforts under this contract, of course, could not be transmitted before completion of the analysis and correlation of all of the data;

therefore, the major conclusions and recommendations are available for the first time in this present report.

1.1.2 The Role of Escape Worthiness in Motor Vehicle Safety

Escape worthiness of motor vehicles can be defined as that characteristic of a motor vehicle manifested in its construction, materials, or geometric arrangement which contributes to the certain, safe and easy egress of its occupants to preserve them from further harm. Thus, the overall philosophy of this research program has been that the burden of assuring this safety for the occupants is ultimately upon the vehicle. The research program itself has been concentrated upon developing means for the initial quantification of the most accessible of the vehicle parameters controlling escape worthiness.

The report on Contract FH-11-7303 which described the pilot studies leading to the present program also included a review of the few available statistics related to escape worthiness. Unfortunately, as was shown in that report, the desired data were neither being reported nor tabulated in usable form. Only for that most serious escape event, fire, could data be obtained. Even those data were so unreliable as to be virtually worthless. These conditions remain unchanged in the two years since publication of that report; with the exception that post-crash fire data have been collected and evaluated. Consequently, neither more reliable information nor sophistication of the earlier account of escape worthiness can be reported here except for the post-crash fire data. Although the magnitude of the problem cannot be convincingly demonstrated, particularly in the absence of any data at all except on the occurrence of fire, there are obvious deficiencies in the escape worthiness of current motor vehicles. Not until a careful evaluation has been made of data requirements according to how they are to be used and not until the entire data collection system has been completely and systematically reconstructed will absolute conviction about the magnitude of almost any traffic safety problem be attainable.

1.1.3 Organization of Effort by Disciplines

This research program was conducted through the University of Oklahoma Research Institute as a multi-disciplinary effort involving the University of Oklahoma College of Health, the School of Industrial Engineering, and the Flame Dynamics Laboratory of the Research Institute. Overall direction and coordination of the research program was maintained at the Flame Dynamics Laboratory as the responsibility of the program manager, Dr. C. M. Sliepcevich, and the project coordinator, Mr. J. N. Ice. Technical management of the project for the National Highway Traffic Safety Administration was accomplished by a series of managers, acting in the following order: Mr. Sumner Meiselman (June-December 1970), Mr. Robert Carter (January-April 1971), Mr. Lynn Bradford (May-August 1971), Mr. Sumner Meiselman (September-December 1971), and Mr. Ray Moody (January-July 1972), all of the Office of Vehicle Structures.

Primary responsibility for the development of the data collection techniques and for the acquisition and assembly of the accident data resided in the College of Health, with the work being conducted at their facility in Oklahoma City under the direction of Dr. W. D. Steen and his assistant, Mr. T. D. Peace. Certain segments of the effort were accomplished with the assistance of the Kansas and Oklahoma Highway Patrols and Kansas and Oklahoma Departments of Health.

Development and direction of the experimental research program on motor vehicle escape worthiness was the responsibility of Dr. J. L. Purswell and Dr. R. F. Krenek of the School of Industrial Engineering on the Norman campus.

Dr. J. R. Welker, Dr. R. G. Rein, Jr., and Dr. C. M. Sliepcevich of the Flame Dynamics Laboratory of the University of Oklahoma Research Institute directed the studies on the flammability of interior materials, vehicle interior fires, fuel modification and fire extinguishment.

1.2 MAJOR ACCOMPLISHMENTS

The experimental effort under the present contract was, as envisioned under the pilot program and in the multi-year research and development plan completed under Contract FH-11-7303, extensive in that it involved the generation and analysis of considerable data, particularly in the flammability and escape test programs. In the several analyses throughout this report, quantitative results appear from time to time in the form of a flammability or escape time. These quantitative levels generally are not the results that are of most significance. They are instead primarily representative demonstrations of the feasibility of a quantifying technique that has been developed. These techniques represent the means by which performance standards may be written and by which performance may be assessed. Therefore, the results from applying these techniques in this program, which are reported herein, do not necessarily represent the minimum levels that should be acceptable; rather the recommendations related to standards which are advanced in this report are to be interpreted as performance measurements and not as prescribed performance levels. Under the multi-year plan presented in the earlier pilot studies, establishment of appropriate levels was to be the objective and result of continuing research and of improved and greatly expanded assessment of the total motor vehicle accident problem. With this cautionary foreword, then, the following brief account of significant results is presented as a preview of the more detailed accounts in succeeding chapters.

A survey of almost 10,000 published documents has reaffirmed the original finding that the literature is inadequate for the purposes of defining minimum safe escape worthiness of motor vehicles. Even the incidence of fire and burn injury cannot be established on a national basis. The problem of potential toxicity of combustion products from burning motor vehicle interior materials is not even being addressed in the open literature. Analysis of data from a large sample of accident reports and other data on fire and submergence collisions in Oklahoma and Kansas again confirms the earlier finding that fatal and injurious effects are more frequent than other studies have estimated. Once the appropriate procedures have been instituted at the levels of effort recommended in the multi-year research and development plan, the problem will be adequately defined to provide a fairly predictive epidemiological model of escape worthiness. Thus, an appropriate model under the plan would not be so limited to fire and submergence related incidents that its virtue and essential concept could be abrogated by vacuous attempts to establish the frequency of fire fatality and injury.

The School of Industrial Engineering has developed a predictive model for escape time which is based upon a set of easily measured vehicle dimensions. The predictive model is effective for a range of vehicle sizes from subcompact through full size, with a varying number of window and door exits, with and without injured passengers, and for both younger and older passenger populations. The model is, however, based upon nearly ideal escape conditions which for all practical purposes assumes that neither the possible deformation of the vehicle nor the physical impairment of the occupants constitutes a hindrance to the escape maneuver. Therefore interpretation of an acceptable minimum escape time will require the incorporation of many more adverse escape conditions. The quantification of the effects of those adverse conditions may be achieved through adherence to the schedules and protocols of the multi-year research and development plan.

The School of Industrial Engineering in its Passenger Car Submergence Studies has also developed a technique for predicting vehicle floating times through the use of two relatively simple test methods for measuring vehicle interior volume and vehicle compartment air-leak rates. Results from the predictive model agree well with those obtained in a brief series of actual submergence tests conducted under Contract FH-11-7303. The methods developed are also useful for determining how a specified allowable sinking time might be achieved through compartment sealing and added flotation.

Another model developed in the submergence studies provides for prediction of deceleration forces, velocities, and vehicle attitudes and depths attained during submergence when a vehicle enters a body of water. This model appears reasonably predictive, but it has not been tested. Confidence in the model can be developed by engaging in a fairly extensive testing program. Such a program would also add to the sophistication and reduce the error of the vehicle sink rate model.

The bus escape worthiness studies have produced methods for estimating escape times from buses for a variety of conditions. Again, the precise level of performance in terms of a maximum allowable escape time has not been investigated in the current program. The bus studies have, however, produced useful data on the design of exits, particularly in the area of realistic allowable operating forces for exit opening mechanisms.

The Flame Dynamics Laboratory has developed a generalized correlation of the ignition data for all the interior materials tested. The concomitant equation for predicting ignition time from the absorbed irradiance, density and thickness of the material is adequate for engineering estimates on flammability. A second and more significant achievement has been the development of the quantitative relationship between ignition characteristics and burning rates. Thus, it is now possible to predict the burning rate of materials that would be observed in any specified burn rate test from the ignition data, the weight of the material per unit area, and an apparatus calibration factor.

The interior fire (enclosure) tests have dramatically demonstrated the potential hazard of burning interior materials if a door or window on the vehicle is left open. For example, even if the headliner passes the FMVSS 302 test, its burning rate in the interior of an open vehicle can under realistic conditions be one to two orders of magnitude greater. Although these tests did not quantify the toxic hazard in combustion products from burning vehicle interior materials, the frequent occurrences of bronchospasm-type reaction among the test personnel left little doubt as to the acuity of the symptom. The intolerable character of the smoke was thus subjectively assessed and indirectly quantified in terms of densities expressed as reductions in light transmission.

A review of the state of the art on fuel modification and current fuel system construction practices clearly demonstrated that the most serious vehicle fire hazard arising from fuel spillage is still unabated despite the modest improvements engendered by the FMVSS 302 standard.

The positive recommendation for requiring some fire extinguishment capacity in new vehicles, which was proposed in the final report on Contract FH-11-7303, now has to be reevaluated. Based solely on the experimental results generated with the severe fires used during this contract, a defensible justification could not be made for the earlier recommendation.

The Flame Dynamics Laboratory also analyzed fire department data on motor vehicle fires from four cities covering two calendar years. The study demonstrated that further analysis of fire department run reports is probably an empty endeavor since the results were not essentially different from the results of earlier surveys. More significant results from such surveys will not be forthcoming because of the general unreliability of the run reports for the purpose of studying motor vehicle fires. More useful results could be obtained with a carefully designed, special reporting procedure, although precise data should still not be expected because of the lack of expertise of firemen in investigative procedures and the destructive nature of fire which eliminates the desired evidence of ignition source. The fire statistics survey also demonstrated that fatalities and injuries from non-motor-fuel-fed fires are fairly infrequent, within the limits of the reporting system. Consequently, it appears that flammable interior materials are most hazardous in the collision environment where even some small amount of fuel spillage will ignite them.

In summary, this research program has now developed the tools for quantification of the hazards of the two severe crash environments of fire and entry into a body of water, and has also produced tools for measurement and evaluation of the vehicle's escape routes, within the limits of an upright vehicle on land.

1.3 FORMAT OF THE REPORT

This final report on Contract FH-11-7512 is organized in two parts in separate volumes. The First Part, consisting of six chapters, is a presentation of the technical research program and the results and conclusions derived from the program. The Second Part contains appendices of ancillary data consisting of a bibliography of pertinent literature, extended accident investigations, detailed tabular and graphical presentation of the data, and detailed mathematical analyses.

Divisions within the First Part, the technical presentation, are organized in the following fashion. Within each chapter, major sections are preceded by an introduction and end with conclusions and recommendations relating to that major section. Chapter Two has two major subdivisions. The first portion, Section 2.1, Literature Review, was the responsibility of Mr. John Ice. Section 2.2, Epidemiological Investigations, reports on investigations conducted under the direction of Dr. W. D. Steen and Mr. T. D. Peace.

Chapter Three is the report on Escape Worthiness Studies completed under the direction of Dr. J. D. Purswell and Dr. R. F. Krenek. This chapter includes five major subdivisions. Section 3.1 provides an account of the studies of Egress from Passenger Cars on Land; Section 3.2 presents the Passenger Vehicle Submergence; Section 3.3 described the Bus Escape Studies; Section 3.4 reports the Human Strength Studies; and Section 3.5 presents an Analysis and Summary of Bus Escape Worthiness.

Chapter Four, Motor Vehicle Flammability and Fire Safety is a report of the research jointly directed by Dr. J. R. Welker, Dr. R. G. Rein, Jr., and Dr. C. M. Sliepcevich. Chapter Four has seven major subdivisions. Section 4.1

discusses the research on Ignition of Interior Materials. Section 4.2 describes the studies on Burning Rates of Interior Materials. Section 4.3 summarizes the tests on Automobile Interior Fires. Sections 4.4 and 4.5 review the status on Fuel Modification and Documentation of Fuels Systems Construction Practices, respectively. Section 4.6 discusses Fire Extinguisher Tests. Section 4.7 presents an Analysis of Municipal Records on Vehicle Fires.

Chapter Five, Recapitulation, is a general summary of the overall research program, which digests the major conclusions and recommendations.

A numbering scheme has been employed for the First Part to facilitate identification of major subdivisions of effort and subsequent reference. Chapter numbers are simply sequential, but section numbers, page numbers, figure numbers, table numbers, and equation numbers carry a chapter-sequence designation of two to five digits. Section and subsection numbers are of the usual type: the first digit represents the chapter number, the second digit indicates the sequential appearance of a major subdivision within the chapter and the third digit indicates the sequence within that section.

Reference notations in the text are enclosed in parentheses and are numbered sequentially beginning with (1) for each chapter; the lists of references cited appear at the end of each chapter. The bibliography for all sections appears as Appendix A of the Second Part.

The Second Part contains four appendices: A: Bibliography; B: Investigation Reports; C: Escape Worthiness Appendices; and D: Flammability Appendices. The number designations consist of a letter and a digit, representing appendix number and the sequence within that appendix.

Attention is called to at least two obvious departures from generally accepted guidelines for technical reports. Both metric and British dimensional units have been used although not indiscriminately. The choice was based, whereever possible, on the system of units which would facilitate the reader's reference to other published material or common practice. The other point is with respect to repetitive statements and references that appear from time to time in the various sections of the report. Such reiterations are not for the purpose of emphasis; rather they are included to accommodate the reader who examines only one or two sections of the entire report.

CHAPTER TWO

ANALYSIS OF INFORMATION

Under the general heading Analysis of Information are included two distinct groups of materials: published and unpublished studies of the general nature of subjects related to the overall concept of escape worthiness and individual case reports of single accidents in the form of police accident reports, newspaper accounts, death certificates, and a limited number of more extensive investigations of single case accidents. Each of these types of information was collected and studied with the principal objective of providing support for the various experimental programs. The study of individual case reports had the secondary purpose of estimating the feasibility of and outlining the general approach to developing an epidemiological model of forced escape from motor vehicles under the most extreme escape conditions of fire in or submergence of the vehicle.

As in the previous effort under Contract FH-11-7303 (1), the information collecting activity has not been exhaustive but has sought to provide a representative cross-section of such information as is generally available. In the instance of information on individual accidents, reporting from six states was sought but not obtained, either because the information was not reported or not retrievable or because of non-cooperation. Information was obtained from two states and is considered adequately representative for immediate purposes. In the instance of literature survey and other information-collecting activities, the effort was exhaustive within the limited resources available for the activity. A far more comprehensive survey would have added little to the final product because of the random and infrequent appearance of critical bits of useable information.

2.1 LITERATURE REVIEW

During the entire course of performance under Contract FH-11-7512, the literature survey initiated under Contract FH-11-7303 was continued, although considerably reduced in allocated level of effort. As a result of the breadth of the total research program, it was necessary to redirect much of the time used previously for this task to coordination activities for the overall program. Nevertheless, it is believed that the essential published information available in the open literature was acquired.

Since the information acquired under the current program has been purely a continuation of the earlier survey, and since no information has been obtained which significantly affects the analysis presented in the final report under Contract FH-11-7303 (1), a similar, extended analysis will not be presented here. Instead, this section will briefly discuss the amount and kinds of literature surveyed, illustrate a desk-top indexing system, and review the results of the only applicable studies of toxicity of pyrolysis products from interior materials. Additionally, a brief description will be given of attempts to find sources of reliable information on the subject of burn injuries incurred in motor vehicle fires.

2.1.1 Publications Reviewed

Within the limits of the level of effort allocated for the literature survey, an effort was made to continue a review of all available documents which might have some relevance to the general subjects of escape worthiness, motor vehicle submergence, and motor vehicle fires. Approximately 10,000 articles, notes, book chapters, research reports, multidisciplinary team reports, and other published items were reviewed for their applicability to the problems. The rate of recovery of useful items was only about eight percent of the total items surveyed, and only a limited number of those could be considered to contain significant pieces of information. This low return on the time investment reflects the general lack of concern for the subjects of interest. At the same time, one should not construe this lack of interest as negligent in nature, but rather as an indication of a necessary assignment of priorities. Additionally, it must be recognized that to a certain extent, studies related to the subjects of interest but conducted by the industry are proprietary in nature and are not made available in the open literature, in part because the studies are not exhaustive and in part because they are often related to customer satisfaction and therefore design decisions based upon market surveys.

A listing of all the acquired items which are considered to be of any utility for the evaluation, characterization, or definition of escape worthiness is presented as Appendix A in the second volume, Part Two, Appendices, of this present report. The citations are grouped according to their association one with another under thirteen arbitrarily designated categories in order that all the related materials for a general subject area will appear together. The thirteen general categories and the numbers of pertinent documents recovered under each are as follows:

Accident Investigation Techniques and Accident Data Analysis Techniques	85
Accident Statistics	17
Studies of Compartment Integrity and Injury Reduction Design Related to Escape Worthiness	133
Studies Related to Occupant Post-Crash Condition Including Panic	80

Studies Related to Body Size and Unimpaired Effort Capabilities	54
Studies Related to Submergence, Including In-Water Escape	39
Studies Related to Bus Escape, Including Other Multiple-Passenger Vehicle Escape	53
Motor Vehicle Fire Studies, Including Case Reports	77
Studies Related to Identification of Fabrics and Interior Materials Flammability	57
Hazards of Toxic Combustion Products and High Temperature	109
Studies of Emulsified and Gelled Safety Fuels	31
Studies of Fuel Characteristics, Fuel Containment and Fuel Ignition Sources	41
Fire Extinguishers and Agents	33

Other documents used in the activities under the program are essentially of the types described in the earlier report cited and consist principally of standards, both voluntary and statutory, standard test methods, research contracts, defect recall campaigns, results of compliance tests, accident investigation case reports, and legislation. Where such items were specifically directed to a subject of interest, they are included in the bibliography in the appendix.

2.1.2 Indexing System

For the purpose of handling the documents and other information collected for the purposes of this research effort, a simplified indexing system was devised using McBee rim-punch index cards. The card is reproduced in Figure 2.1 Use of the card is self-explanatory, since with the exception of the accession number, all subjects are direct-coded; that is, a key word rather than a numerical code is used. The accession number is entered on the card by punching out the holes for

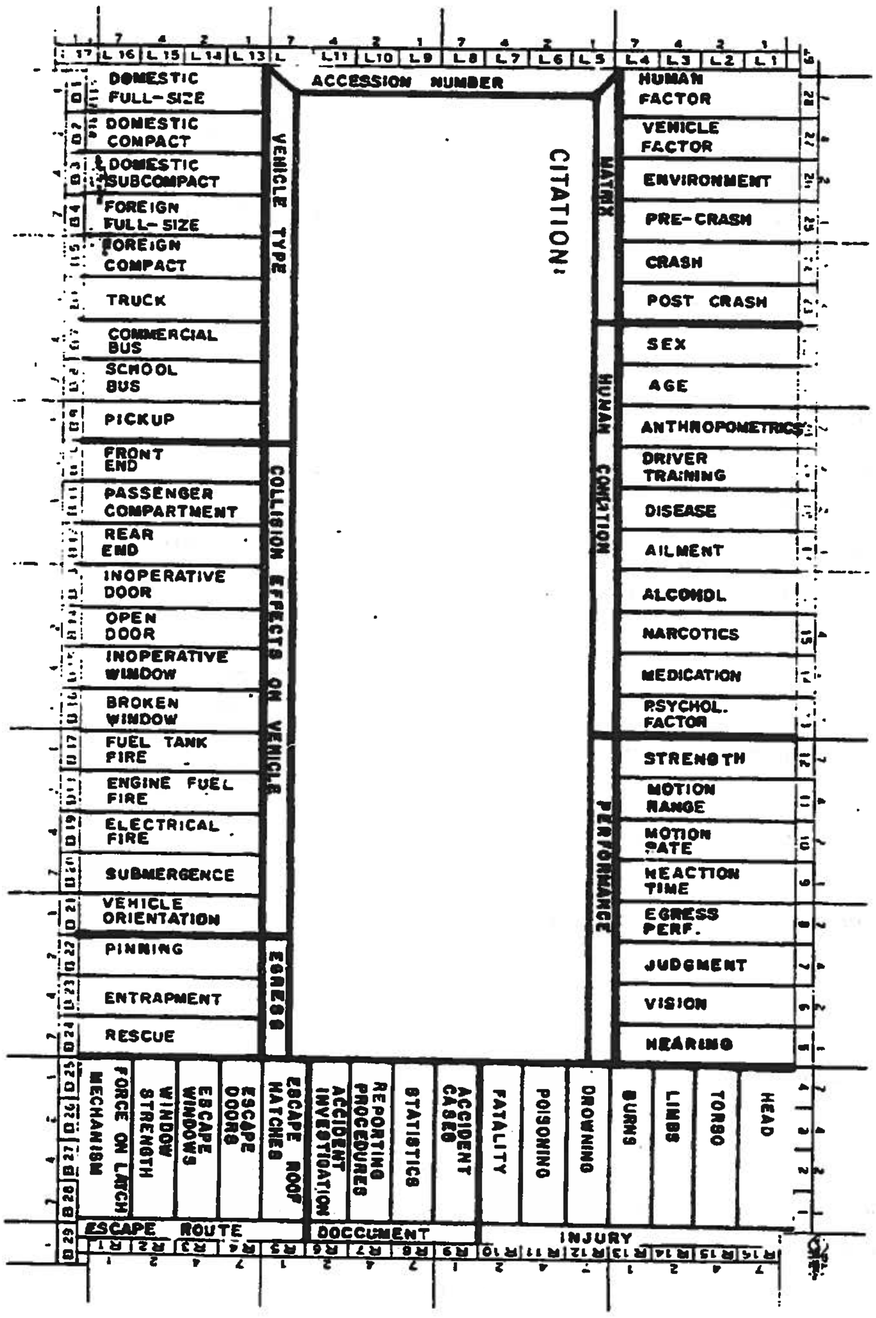


Figure 2.1. Rim-punch index card for subject indexing escape-worthiness-related literature.

the 7-4-2-1 code in an additive fashion to designate a digit. Thus for number 3, the 2 and 1 holes are punched. For the subject areas, the holes for the appropriate key words describing the document are punched out. Retrieval is achieved by repetitive needle sorting, with the desired items dropping away from the needle.

This system is perhaps slightly more time-consuming in the retrieval phase, but it offers a very inexpensive, desk-top capability for subject indexing of small files, such as might be useful to an individual responsible for the general area of escape worthiness. Neither this card nor the rim-punch system are necessarily recommended for agency-wide or laboratory-wide use, since files in excess of 10,000 documents are too cumbersome for this system. The system is presented here only in the event that some individual might wish to implement it for his own use. It offers fairly selective subject indexing, bibliographic citation, and space for an abstract on the back for convenience in scanning and so is optimum for desk-top use. The system is not readily suitable for duplication in coded form.

Although the indexing system was devised and has been tested, it was never fully instituted for the literature survey under this contract.

2.1.3 Civil Aeromedical Institute Studies of the Toxicity of Pyrolysis Products

In spite of the fact that occasional papers appear implying a discussion of short-time toxicity of pyrolysis products (e.g., References 2 and 3), no real interest has yet been generated in this subject. As reported under Contract FH-11-7303, however, at least one agency, the Civil Aeromedical Institute of the Federal Aviation Administration, is exploring the potential problem as it applies for aircraft interior materials of construction.

The Civil Aeromedical Institute is continuing its investigations of short-time toxicity of the combustion products of burning aircraft interior materials, but at a considerably lower level of effort than was envisioned in the original conception of the program. Consequently, the expected enlightenment from their program on the nature and magnitude of the toxicity hazard has not materialized.

Because of the requirement for specialized equipment to withstand the corrosive gases expected to be generated, the animal exposures for the Civil Aeromedical Institute's program are being conducted at the Toxic Hazards Research Unit of the USAF Aerospace Medical Research Laboratories at Wright-Patterson Air Force Base, Ohio. One relatively low-keyed study has been completed; another is in the final reporting stage; and a third is just beginning.

The completed study (4, 5, 6) involved determination of LC_{50} levels of hydrogen fluoride (HF), hydrogen chloride (HCl), nitrogen dioxide (NO_2), hydrogen cyanide (HCN), and carbon monoxide (CO) in mice and rats. The studies were done by exposing the animals for five minutes to varying atmospheric concentrations of the gases, singly and in combination with carbon monoxide at a CO concentration adequate to produce a 25 percent carboxyhemoglobin level. Determinations of LC_{50} concentration levels (Lethal Concentration for 50 percent of the test animals) were obtained for all the gases used. The 5-minute CO concentration for 25 percent COHb level in mice was determined to be 1,500 ppm, and in rats, 2,100 ppm. Approximate LC_{50} concentrations in parts per million for the gases and mixtures were as follows:

	HF	HF+CO	HCl	HCl+CO	NO_2	NO_2+CO	HCN	HCN+CO
Rats:	18,200	18,208	40,989	39,010	831	1,140	503	467
Mice:	6,246	6,670	13,745	10,663	1,880	1,644	323	289

The toxicity ranking of the four materials is HCN, NO_2, HF, and HCl in decreasing order. Carbon monoxide concentrations at these levels do not enhance the toxic response to the four substances tested.

The second study was an investigation of the effects on pulmonary function of a sub-lethal dosage of HCl, NO_2, and HF in monkeys (Macaca mulatta). At these dosages, no immediately incapacitating effects were observed. For the suspected longer range effects, the findings were inconclusive. However, observation of chemical burns in the alveolar bronchi, significant levels of edema, and emphysematic symptoms was adequate to warrant continued interest in these effects. A more critical study will probably reveal both immediate and delayed interference with pulmonary function and may display delayed terminal injury. The results of the completed experiments may be retained in-house pending completion of a more extensive investigation of this subject.

The third study which is just underway (July 1972) is limited to an investigation of the toxic effects of carbon monoxide, hydrogen cyanide, and the two gases combined. This investigation will attempt to determine in rats the 5-minute LC_{16}, LC_{50}, and LC_{86} levels of the two gases single and combined. This study also involves determination of the tissue and blood level concentrations corresponding to the three LC levels. The results of this study should allow specification of tolerable atmospheres of these gases and should also aid in the evaluation of these gaseous environments presently being generated in aircraft fires through comparison with necropsy data. This study is scheduled for completion in early 1973.

The precise extent of the hazard of combustion products, even from aircraft material, is not yet clear from these studies, because the precise method of extrapolation to concentrations tolerable to humans is not yet clear. In a study discussed earlier under Contract FH-11-7303 (1), for example, the 30 minute limit for human exposure to HF is 50-250 ppm and for HCN is 100-200 ppm. The limits are approximately equal. Yet the hydrogen fluoride LC_{50} for rats is almost 36 times the HCN LC_{50} for rats at the 5 minute exposure rate. In mice the HF LC_{50} is 20 times the HCN LC_{50}. The 30-minute human limit for HCl is 1000-2000 ppm and for NO_2 about 200-700, or about one-fifth the HCl limit. The 5-minute LC_{50} level of HCl in rats, however, is about 41,000 ppm, while the NO_2 LC_{50} is only 830, a ratio of one to fifty instead of one to five. For mice, the LC_{50} ratios are only about one to ten (NO_2: 1,880; HCl: 13,745). The question that must be answered is whether the 5-minute lethality in humans for NO_2, for example, is in fact fifty times as high as the comparable lethality of hydrogen chloride or only fire times as high. The course of action with respect to an allowable concentration will probably have to be rather arbitrary and most certainly highly conservative, perhaps to the extent of specifying the 30-minute dangerous-fatal limits for an expected total 5-minute escape time.

The probability of thirty-minute concentrations being attained in a 5-minute flaming period, assuming that the concentrations of the gases of interest were generated from motor vehicle interior materials at the same rate as from aircraft materials, would appear to be fairly high since these concentrations would involve the combustion of about 60 square inches of material in a 5-minute period (assuming no atmospheric losses). To burn this area of material in this time period, the burning would progress at a rate of 4 inches in five minutes. If the burning rate of materials producing these concentrations were 4 inches per minute, then the dangerous-fatal 30-minute concentrations suggested as a specification would be attained in one minute, and would require escape in one minute (disregarding breath-holding). As was shown in Section 2.1.8 of the earlier report, the only 30-minute dangerous-fatal concentrations attained for aircraft materials were those for HCl, HF, and HCN (borderline). The NO_2 30-minute limit was not attained. The tests under discussion were those on the individual material that produced a maximum concentration. These concentrations of all the gases were never obtained from a single interior material.

In actual practice, of course, with windows open or the compartment not intact, even if the toxic limits remained low, after five minutes of burning, the vehicle interior temperature would have exceeded tolerable limits. In one minute at 4-inches per minute, burning 60 square inches of a modacrylic rug material (or about 70 grams of material) the HCN 30-minute dangerous-fatal limit would be exceeded, and the roughly estimated interior temperature rise in the 120 cubic foot compartment would be about 70-80 degrees Fahrenheit, assuming a concomitant heating of about 100 lbs of other materials (metals, unburned seats, etc.).

The entire question of the toxicity of the combustion products from burning motor vehicle interior materials may nevertheless be academic, since in the enclosure tests conducted under the present contract and described in Section 4.3 of this report, using calorimetric tubes for the gas analysis, no significant concentrations of any of these or several other toxic gases were ever observed. It should also be kept in mind that these observations were made under fire conditions where the oxygen concentration never fell below 13 percent and usually, the fire ceased to burn. With a lowered oxygen content, the other gas concentrations would be expected to be higher than would occur in a normal atmospheric oxygen concentration. The question implicit here is whether more sophisticated instrumentation would demonstrate the presence of these toxic gases. Such instrumentation should also demonstrate the cause of the debilitating effects of smoke described in Section 4.3.

2.1.4 Availability of Reliable Statistics on Occupant Non-Fatal Injuries in Motor Vehicle Fires

During the course of this contract, individuals in NHTSA expressed an interest in the subject of burn injury and burn fatalities from burning automobile interior materials where no motor fuel was involved in the fire. A number of burn injury centers and other agencies were contacted to attempt to determine whether national statistics on such injuries and fatalities could be developed.

All of the burn centers contacted were unaware of any attempt to develop such information and had no suggestions as to how such information could be acquired. All did, however, recommend that a likely source was the National Burn Information Exchange at the University of Michigan, since they each reported their experience to the Exchange.

After numerous attempts to contact officials of the National Burn Information Exchange, both by mail and telephone, contact was established for one brief telephone conversation with an associate of the director of the Exchange. This individual reported that he did not believe the information was presently available anywhere, and that he did not believe that the reporting system in use by the Exchange was presently designed in such fashion as to yield an appropriate response to the question. The primary difficulty at the present time is that there is not adequate depth in reporting to discriminate between motor-fuel-fed and non-motor-fuel-fed fires. In this system, at least, a distinction can be made between motor vehicle fire and other fire injury. Although a request was submitted through this individual for more detailed description of their files and reporting procedures to be sent by mail, no further response was received and contact could not be re-established.

Considerably later in the contract period, a document was obtained which does contain some information descriptive of the National Burn Information Exchange. Included in this document, a Senate Committee Hearing On "Flammable Fabrics and Other Fire Hazards to Older Americans" (7) is a chart illustrating for 30 injury sources the frequency of each source in about half of the NBIE file. "Land Vehicle Crashes" ranks eighth as a cause of burn injury, accounting for 4.5 percent of the NBIE flame sample. This relatively low percentage of injuries as compared to frequency of fatalities in motor vehicle fires, as shown in a later section of this chapter, may be accounted for as a function of relative lethality based upon the observed ratio of fire fatalities to fire injury in motor vehicles as compared to other fire sources. In motor vehicle fires in general, the occupants die and so never appear in burn injury samples.

The two other agencies contacted which appeared most able at some future date to develop the data desired were the Mortality Branch of the National Center for Health Statistics of the Public Health Service, Department of Health, Education and Welfare, and the Injury Data Control Center of the Bureau of Product Safety in the Federal Drug Administration. Both these agencies reported that the information is not presently available. The Mortality Branch of the Center for Health Statistics believed that at some future date, some data on fatalities might be developed, but at best, the response was noncommittal as to feasibility. The Injury Data Control Center reported that when their National Electronic Injury Surveillance System (NEISS) is fully operational in the immediate future, the desired statistics could be obtained as a special project.

The only acceptable conclusions with respect to the question are that the information is not presently available from any source and that there is at least a potential source for developing these statistics in the near future but at relatively high cost. Despite the need for this information extreme caution should be exercised in undertaking to collect it because of the difficulty of obtaining reliable raw data.

2.1.5 Conclusions and Recommendations

1. Information on the toxicity of pyrolysis products from automobile interior materials and on the products being generated is still not available. The recommendation advanced in the report on Contract FH-11-7303 is still appropriate: experimental programs should be initiated complementing those being conducted by the Civil Aeromedical Institute, but at a higher level of effort. The question of whether toxic materials are generated should be researched at a level of funding adequate to provide for the use of sophisticated instrumentation.
2. Information for developing statistics on burn injuries and deaths in motor vehicle fires where no fuel is involved is not now available and will not be developed under any existing program. Depending upon NHTSA's requirements and the cost, a system for acquiring this information can be developed.

2.2 EPIDEMIOLOGICAL INVESTIGATION

These efforts were intended as a feasibility study to determine the current availability of information related to escape worthiness of motor vehicles. The primary sources of data were police accident reports and death certificates. In order that an identifiable segment of escape worthiness situations could be studied, post-crash fire and submergence collisions were selected.

2.2.1 Data Acquisition

The primary activity of the College of Health during the contract period has been conducting pilot trials of test techniques for retrieval of crash accident information related to escape worthiness and occupant survival. Obviously, the most critical component of this program has been the availability and quality of data which would help identify critical escape worthiness parameters. Initial efforts under an earlier contract, FH-11-7303, were to determine whether motor vehicle crash fire and submergence data were available on a national basis. The primary activity under that contract (as developed through consultation with the contract technical manager) involved the evaluation of post-crash fire or submergence collisions, which represent the most dangerous events affecting escape worthiness. It was believed that these collisions would be well reported and that a reasonable sample of escape-involved accidents could therefore be acquired. It was decided that the development of statistical information and a pilot epidemiological model could be limited to these two post-crash situations.

Under contract FH-11-7303, a questionnaire was submitted to the appropriate offices in the fifty states and the

District of Columbia. This questionnaire sought information on the availability of post-crash fire and submergence accident reports from these authorities.

Based on the results of the survey that reporting was often either incomplete or non-existent, it was concluded that there was little possibility of undertaking a nation-wide study of post-crash fire and submergence accidents. It was concluded, however, that an effort could be made to obtain reports from a few select states.

The present contract effort involved a more extensive pilot trial of the data acquisition techniques used in the earlier effort. This report presents the data collection methodology and an analysis of the data with an outline of a pilot epidemiological model.

2.2.2 Sources of Data

Efforts aimed at actual data collection and analysis under FH-11-7303 were initiated in the state of Oklahoma. The system was retained in this state, and work under the present contract, FH-11-7512, involved an attempted extension of this program into other states to provide a representative sample of the post-crash fire and post-crash submergence experience for the development of a pilot epidemiological model.

Selection of states was based upon information collected by the earlier questionnaire. Completed questionnaires were returned by 43 states. The states were then evaluated for:

1. Availability of reporting.
2. Frequency of reporting.
3. Number of accidents (overall rates).
4. Geographical characteristics of the state.
5. Demographical characteristics of the state.
6. Other environmental influences.

All states that indicated that fire and/or submergence are always or usually reported on a routine basis (by police investigation forms) were isolated and all others were eliminated from consideration. Questionnaires from the candidate states were then screened to determine whether reports could be obtained from these states. Nineteen states fit the criteria of (1) fires and submergence were always or usually reported on a routine basis, and (2) reports were alleged to be available. The states that always receive reports on both fire and submergence included Kansas, Florida, Kentucky, Arkansas, Alaska, South Carolina, and Tennessee. Those states that indicated both fire and submergence are usually reported included New York, Alabama, Oregon, Maine, Mississippi, Maryland, Georgia, Connecticut, Wyoming, Utah, North Carolina, and Pennsylvania.

Four states were eliminated due to the small number of total accidents reported per year: Alaska, Maine, Wyoming, and Utah.

(1) Tennessee was selected because the state has many variations in terrain and covers such a large geographic area (the three states of Tennessee). Kentucky, Alabama, Georgia, and North Carolina were eliminated because of their gross similarity to Tennessee and the fact that they border two selected states that had indicated the ability to retrieve reports by machine sort, (2) Florida and (3) South Carolina. (4) Kansas was selected to represent the center United States region; (5) Pennsylvania was selected to provide a state with large population and variations in terrain. (6) Connecticut was selected to represent a traffic sample of eastern suburbia. (7) Oregon was selected because of their prior interest in submergence and to represent the west coast region. The only void geographically and demographically was the northern middle sections of the United States. None of the northern middle states was eligible under the selection criteria. The absence of a northern middle tier state also contributed to the selection of Kansas.

It was anticipated that these seven states in addition to Oklahoma would provide an adequate sample of accident experience to provide a base for the testing of hypotheses and the subsequent model development. However, when an active program of seeking data from the seven states was initiated, it was found that many responses to the questionnaire were either misleading or in error. Only three states in addition to Oklahoma claimed to be able to provide the data required. They were Kansas, Tennessee and Connecticut. Reasons for other states being unable to participate in the program included confidentiality of records (Oregon and Pennsylvania) and the need for extensive reprogramming or alteration of machine capabilities (Florida and South Carolina).

Therefore, the data collection efforts under contract FH-11-7512 were begun with cooperation programs in four states: Oklahoma, Kansas, Tennessee and Connecticut. Reporting from Tennessee and Connecticut was not adequate in any respect. These states were not able to provide reports on a routine basis after the initiation of the data collection program; therefore, the data included in this report is limited to that reported by Oklahoma and Kansas.

2.2.3 Data Collection in Oklahoma

The Oklahoma Department of Public Safety and State Department of Health have given complete cooperation in the attempt to retrieve reports on post-crash fire and submergence. The system utilized in this state involves data from four sources and was finalized in December 1969 to begin on January 1, 1970.

<u>Accident reports</u> were submitted by the Department of Public Safety. These reports were screened during the routine coding procedures at the Department and certified copies of all accident reports involving fire or submergence were submitted to the College of Health. These reports were those completed by the investigating law enforcement officer and

have a special block to be checked by the officer when fire occurs (see examples in Appendix B in the second volume of this report). This special "fire block" was added to the report form in 1969 as a result of interest by the Department of Public Safety in early cooperative efforts with the Research Institute. As a matter of routine, the narrative portion of all reports was also reviewed by the Department's coding clerks. Those which mentioned fire or submergence, either by a "yes" in the fire block or mention in the narrative, were copied and submitted for this study.

Death certificates are screened for coding by the Oklahoma State Department of Health. During this procedure, all death certificates which indicated that the fatal injury occurred in a motor vehicle were screened for burns or drowning as a principal or contributing cause of death. An abstract of each such death certificate was sent to the College of Health.

Newspaper clippings were provided by a statewide clipping service. This service included weekly as well as daily publications. All clippings which mentioned fire or water in relation to a motor vehicle accident were provided to the project.

These three primary systems (accident report, death certificates, and newspaper coverage) operated independently, and the specific cases were matched during tabulation. In the event that a collision was not reported from all three sources, inquiry was made and the missing report obtained. This system provided two sources of reporting for non-fatal collisions and three sources for fatal collisions.

In-depth evaluations of certain aspects of a few selected post-crash fire and submergence collisions were conducted by the staff to check further the validity of data from the reporting systems (Appendix B). In addition, these investigations provided clues to a considerable amount of critical data related to escape worthiness which was not available from the reporting systems. Data was collected in Oklahoma utilizing both retrospective reports and special evaluations during calendar years 1970 and 1971.

2.2.4 Analysis of Oklahoma Post-Crash Fire Data

These data represent two full years of reporting by the Oklahoma Department of Public Safety and the Oklahoma State Department of Health. The period covered is all of calendar years 1970 and 1971 for accident reports and death certificates submitted by these two agencies. The statewide newspaper clipping service has been utilized since September 1, 1970. This clipping service has supplied both new, unknown accidents (i.e., reports were not retrieved) involving post-crash fire as well as clippings on known accidents.

One hundred and forty-five post-crash fire accidents were reported during 1970 and 1971 (Table 2.1). During this period, there was a total of 129,366 non-pedestrian motor vehicle accidents reported in the state of Oklahoma (excludes pedestrians, motorcycle, motorbike and animal). When we

TABLE 2.1

MOTOR VEHICLE COLLISIONS INVOLVING POST-CRASH FIRE
OKLAHOMA 1970 AND 1971

	Number of Collisions	Fatalities	Percent of all Fatalities	Injuries	Not Injured in Burned Vehicle
All Accidents State Total*	129,366	1391	100.0	37,554	NA
Post Crash Fire	145	66	4.7	113	40

*Non-pedestrian accidents. Also excludes motorcycle, motorbike, etc.

consider the simple occurrence of post-crash fire in relation to the total accidents in this state, there does not appear to be a significant problem with these collisions. However, when we examine fatalities associated with post-crash fire, it becomes evident that forced escape situations prompted by post-crash fire are a more important problem.

Sixty-six (66) fatalities or 4.7 percent of the total 1,391 non-pedestrian fatalities in the two-year period resulted from collisions where the victim was the occupant of a vehicle that burned after the initial crash.

It is interesting to note that while 129,366 accidents produced 1,391 fatalities and 37,554 injuries, 145 post-crash fire accidents produced 66 fatalities and 113 injuries. It appears that while one fatality per 93 accidents is experienced for all non-pedestrian accidents, post-crash fire accidents produce <u>almost one fatality for every two such accidents</u>.

An examination of the total (145) post-crash fire collisions reveals that there were 49 collisions with a fatality in a burned vehicle, 55 with injury in a burned vehicle and 41 with no injury in a burned vehicle (Table 2.2). This would indicate about a 33 percent chance of experiencing either a fatality, an injury or no injury in such a collision.

TABLE 2.2

DISTRIBUTION OF POST-CRASH FIRE COLLISIONS
BY MOST SEVERE INJURY
OKLAHOMA 1970 AND 1971

Collisions with Fatality in Burned Car	Collisions with Injury in Burned Car	Collisions with No Injury in Burned Car	Total Collisions
49 66 fatalities	55 113 injuries	41 40 uninjured	145

Since all uninjured occupants are not reported on accident reports, the 40 not injured occupants must be considered as only a portion of the total.

Death certificates for the fatalities in vehicles that burned post-crash were examined for cause of death (Table 2.3). Of 66 such deaths, 46 listed burns as the principle or contributing cause of death. The remaining 20 fatalities were listed as caused by head injury, internal injury, or multiple injuries. However, some causes were listed as "automobile accident syndrome," "accident," or "automobile accident" with "head" or "internal" as contributing causes. It is probable that a portion of these victims received burns. Even though it is equally probable that some victims suffered impact injuries (some were ejected), with the advent of improved vehicle crash worthiness, this group will become a more significant part of the escape worthiness problem. In the future these persons probably will be alive but may continue to be exposed to a severe fire environment. Therefore, all fatalities associated with post-crash fire should be considered in attempting to identify fatalities which may be the result of inadequate escape worthiness of vehicles.

TABLE 2.3

DISTRIBUTION OF 66 FATALITIES BY INJURY FOR COLLISIONS INVOLVING POST-CRASH FIRE*
OKLAHOMA 1970 AND 1971

Total Fatalities	Fatal Injuries			
	Head	Internal	Head Plus Other	Burns
66	4	5	11	46

*Source: Death certificates.

Some confusion appears to have been introduced by this practice of collecting information on all fatalities associated with post-crash fire in a motor vehicle. This confusion arose primarily because of the misconception that the present contract effort was concerned with post-crash burn fatalities alone. What in fact was of concern was finding actual collisions <u>in which an escape hazard existed</u>. Consequently, agreements with the contract technical manager specified as retrieval keys the two most readily identifiable escape hazards, fire and submergence. Under this selection criterion, reports were acquired on 66 fatalities attributable in part to the single escape hazard of fire. These 66 fatalities associated with post-crash fire accounted for 4.7 percent of all non-pedestrian fatalities in Oklahoma for the two-year period. The official primary cause of death for 46 of those fatalities was burns. These 46 fatalities constitute 3.3 percent of all non-pedestrian fatalities. What is significant about these numbers is not that only about 3 percent of the motor vehicle fatalities are unequivocally attributable to fire, but that almost 5 percent of all non-pedestrian fatalities are to some extent attributable to a single problem of escape worthiness.

There were 113 non-fatal injuries reported on standard accident reports by the Oklahoma Highway Patrol (OHP) for vehicles that burned post-crash (Table 2.4). These reports indicate that over half of the non-fatal injured occupants were incapacitated, thus decreasing the likelihood of unassisted escape. The definitions used by the OHP are as follows:

> "(A) Incapacitating injury--It covers instances in which the person described is unable to walk or drive or to perform normal activities he could perform prior to the collision.
>
> (B) Non-incapacitating evident injury--It covers a visible injury that does not incapacitate the victim.

It includes injuries made 'evident' by oozing of blood through clothing, etc.

(C) Possible injury--When the victim complains of pain without visible signs of injury."

These determinations are made by the trooper at the scene and without the benefit of consultation with medical authorities. There is no reasonable means of determining the general type of injury suffered (burns or impact) from any public record.

TABLE 2.4

DISTRIBUTION OF 113 NON-FATALITIES BY SEVERITY OF INJURY FOR COLLISIONS INVOLVING POST-CRASH FIRE*
OKLAHOMA 1970 AND 1971

Site of Injury	Incapacitated	Not Incapacitated	Possible Injury	Total
Head	11	9	1	21
Trunk-External	0	1	0	1
Trunk-Internal	4	2	2	8
Arm and/or Leg	5	5	3	13
Head Plus Other	39	27	4	70
TOTAL	59	44	10	113

*Source: Accident reports.

A comparison of post-crash fire fatalities with all non-pedestrian fatalities in Oklahoma reveals that the age distribution of drivers and passengers is similar (Table 2.5). The distribution of fatal passengers by sex is also comparable; however, for drivers there appears to be a difference. Whereas the ratio of fatal male drivers to fatal female drivers in all fatal accidents is 4.5 to one, for the post-crash fire collisions the rates are 40 to one.

TABLE 2.5

DRIVERS AND PASSENGERS KILLED IN ALL ACCIDENTS* AND IN POST-CRASH FIRE ACCIDENTS DISTRIBUTION BY AGE AND SEX OKLAHOMA 1970 AND 1971

Age Groups	Drivers Killed				Passengers Killed			
	State Total		Post-Crash Fire		State Total		Post-Crash Fire	
	Male	Female	Male	Female	Male	Female	Male	Female
0-4	0	0	0	0	23	17	0	1
5-13	3	0	0	0	14	21	1	0
14-15	2	0	0	0	7	11	0	0
16	14	2	1	0	15	6	1	0
17-21	122	22	8	1	79	39	6	3
22-27	94	18	5	0	36	22	1	2
28-33	54	15	4	0	11	9	0	0
34-39	59	18	3	0	9	14	1	1
40-44	49	9	9	0	5	11	1	0
45-54	85	24	4	0	21	22	2	0
55-64	86	25	4	0	20	28	0	1
65-74	82	14	2	0	22	28	2	0
75-	51	8	0	0	12	21	1	0
Not Stated	0	0	0	0	6	6	0	1
TOTAL	701	155	40	1	280	255	16	9

*Non-pedestrian accidents.

Position in the vehicle for all occupants (fatal and injured) for post-crash fire collisions is similar to the total experience in Oklahoma for position in the vehicle (Table 2.6). The rates for drivers versus passenger are also similar: drivers constitute 55 percent of the fatal and injured occupants for all accidents and 58 percent in the post-crash fire collisions. Unfortunately, adequate data are not available for non-injured occupants for the post-crash fire collisions or overall collisions. Only forty uninjured occupants were identified in the post-crash fire group of 219 occupants, and then only by virtue of being listed as witnesses in the vehicle or as drivers in non-injury post-crash fire collisions. These forty occupants probably do not represent the total uninjured occupants in the vehicles. As stated before, information on all occupants in motor vehicle accidents is not supplied by present accident report procedures. Only drivers and injured occupants are consistently reported.

TABLE 2.6

DISTRIBUTION OF OCCUPANTS BY INJURY SEVERITY AND POSITION IN VEHICLE
POST-CRASH FIRE VERSUS ALL NON-PEDESTRIAN ACCIDENTS
OKLAHOMA 1970 AND 1971

Occupants	Left Front	Center Front	Right Front	Left Rear	Center Rear	Right Rear	Not Stated	Total
Post-Crash Fire								
Killed	42	2	17	0	4	1	0	66
Injured	63	3	25	8	7	5	2	113
No Inj.	37	1	2	0	0	0	0	40
All Accidents								
Killed	856	55	342	31	28	48	31	1391
Injured	20,670	2388	9697	1260	779	1559	1207	37,554

The distribution of post-crash fire collisions by time of day and location reveals that even though the location data for non-fatal collisions are not unusual, fatal collisions occur in rural areas 85 percent of the time (Table 2.7). Rural occurrence is clearly characteristic of fatal post-crash fires since the usual experience for all fatal accidents is approximately two rural to one urban. The occurrence of crash fire fatalities in rural areas is perhaps not so much a reflection of an accident collision phenomenon, but it may reveal that rescue is unlikely in rural locations. Herein lies a significant escape worthiness parameter for further study. Are occupants of burning vehicles in urban areas rescued? Do occupants in rural areas perish because no one is available to assist them?

TABLE 2.7

TIME AND LOCATION DISTRIBUTION FOR 145
POST-CRASH FIRE COLLISIONS
OKLAHOMA 1970 AND 1971

Time	Rural		Urban*		Total	
	Fatal	Non-Fatal	Fatal	Non-Fatal	Fatal	Non-Fatal
6:00-7:59 AM	5	6	0	4	5	10
8:00-9:59 AM	1	3	0	3	1	6
10:00-11:59	2	3	0	6	2	9
12:00-1:59 PM	2	3	1	2	3	5
2:00-3:59 PM	3	8	1	3	4	11
4:00-5:59 PM	3	2	1	4	4	6
6:00-7:59 PM	3	7	0	2	3	9
8:00-9:59 PM	4	3	1	4	5	7
10:00-11:59	5	8	0	4	5	12
12:00-1:59 AM	6	11	1	3	7	14
2:00-3:59 AM	3	5	2	0	5	5
4:00-5:59 AM	3	3	0	1	3	4
TOTAL	40	62	7	36	47	98

*All collisions occurring within the city limits of an incorporated town including those on interstate highway within city limits.

It appears that the distribution by time of day of rural post-crash fire collisions is not different from that of urban post-crash fire collisions. That is to say, the collisions occur at night in approximately the same number as during the day in both urban and rural areas.

Data presented in Table 2.8 show the distribution of the 145 post-crash fire collisions by location, severity and month of occurrence. No seasonal effect is apparent. In the preparation of Tables 2.7 and 2.8, the distinction between urban and rural location is not particularly reliable for the "urban" data due to the fact that large areas of an essentially rural character occur within the city limits of many Oklahoma cities.

TABLE 2.8

DISTRIBUTION OF 145 POST-CRASH FIRE COLLISIONS BY LOCATION AND MONTH OKLAHOMA 1970 AND 1971

Month	Rural		Urban*		Total	
	Fatal	Non-Fatal	Fatal	Non-Fatal	Fatal	Non-Fatal
January	2	8	0	1	2	9
February	1	2	0	0	1	2
March	2	4	0	3	2	7
April	3	4	0	5	3	9
May	3	3	3	0	6	3
June	3	8	0	5	3	13
July	6	6	1	5	7	11
August	5	6	1	4	6	10
September	8	4	0	3	8	7
October	1	8	0	1	1	9
November	3	4	1	6	4	10
December	3	5	1	3	4	8
TOTALS	40	62	7	36	47	98

*All collisions occurring within the city limits of an incorporated town including those on interstate highways within city limits.

Passenger cars that burned totaled 101 during 1970 and 1971 in Oklahoma (Table 2.9). By manufacturer they included: General Motors, 50; Ford, 24; Chrysler, 16; American Motors, 4; and Volkswagen, 6. Even though the total number of burned vehicles is low, it would be interesting to compare this information with the population at risk (total passenger cars in Oklahoma) by manufacturer. However, this information is not tabulated by the only agency that collects the appropriate data.

TABLE 2.9

PASSENGER CARS THAT BURNED POST-CRASH
DISTRIBUTION BY MANUFACTURER
OKLAHOMA 1970 AND 1971

	American Motors	General Motors	Ford Motor Company	Chrysler Corp.	Volkswagen	Porsche	Total
Fatality Inside	2	12	9	5	1	0	29
No Fatality Inside	2	38	15	11	5	1	72
TOTAL	4	50	24	16	6	1	101

Pickup trucks accounted for 24 of the vehicles that burned, distributed as follows: General Motors, 14; Ford, 7; Chrysler, 1; and International, 2 (Table 2.10). Large commercial trucks account for 29 of the total 154 vehicles that burned post-crash (Table 2.11).

The distribution of burned vehicles by type revealed that passenger cars, pickup trucks and commercial trucks accounted for 65, 16 and 18 percent, respectively.

Sixty-five (65) of the 154 total burned vehicles were 1968 or newer models (Table 2.12), or 42 percent of the total vehicles. It appears that newer vehicles (1968-72) represent a higher proportion of the post-crash fire experience. However, this disproportion may be a reflection of these vehicles being driven at higher speeds and being involved in more severe collisions or perhaps is partially a reflection of exposure (miles driven).

TABLE 2.10

PICKUP TRUCKS THAT BURNED POST-CRASH DISTRIBUTION BY MANUFACTURER OKLAHOMA 1970 AND 1971

	General Motors	Ford Motor Company	Chrysler Corp	Intrntl Harvester	Total
Fatality Inside	9	4	1 Winnebago	1	15
No Fatality Inside	5	3	0	1	9
TOTAL	14	7	1	2	24

TABLE 2.11

COMMERCIAL TRUCKS THAT BURNED POST-CRASH DISTRIBUTION BY MANUFACTURER OKLAHOMA 1970 AND 1971

	Ken-worth	Intl Hvtr	REO	White	Mack	Ford	GMC	Chry Corp	Total
Fatality Inside	0	2	0	3	0	0	0	0	5
No Fatal. Inside	2	6	1	4	3	1	5	2	24
TOTAL	2	8	1	7	3	1	5	2	29

TABLE 2.12

VEHICLES THAT BURNED POST-CRASH, DISTRIBUTION BY MODEL YEAR OKLAHOMA 1970 AND 1971

	1972	1971	1970	1969	1968	1967	1966	1965	1964	1963 & older	Total
Passenger Cars	0	3	8	20	6	11	6	8	5	34	101
Pickups	1	4	4	3	2	1	2	1	1	5	24
Commercial Trucks	0	1	4	9	0	0	5	4	0	6	29
TOTAL	1	8	16	32	8	12	13	13	6	46	154

TABLE 2.13

RELATIONSHIP OF INJURY SEVERITY TO FINAL VEHICLE POSITION FOR 145 POST-CRASH FIRE COLLISIONS INVOLVING 154 VEHICLES OKLAHOMA 1970 AND 1971

Position Vehicle Came to Rest	No. of Vehicles		Fatalities		Injuries		No Injury	
	Number	Percent	Number	Percent	Number	Percent	Number	Percent
Vehicle Upright	107	69.5	42	63.6	76	67.2	29	72.5
Vehicle on Side or Top	42	27.3	22	33.3	34	30.0	10	25.0
Unknown	5	3.2	2	3.1	3	2.7	1	2.5
TOTAL	154	100.0	66	100.0	113	100.0	40	100.0

The vehicles that burned post-crash came to rest on their top or side 27.3 percent of the time (Table 2.13). It is not possible to acquire comparable data on final vehicle position for the state or for the nation. This type of occurrence (vehicle on side or top) produced 33.3 percent of all fatalities associated with post-crash fire. Based on a limited number of in-depth evaluations, it appears that when a pickup comes to rest on its side or top the hazard is particularly serious. There are two primary reasons for this excessive hazard:

1. The fuel tank is located within the passenger compartment.
2. The filler neck appears to be very susceptible to damage in a rollover.

When a pickup comes to rest on the side, there is only one escape exit available--the top door or window. This situation is further complicated by the weight of the door and the distance to be reached for escape. When a pickup comes to rest on its side, unassisted escape is practically impossible. The hazard encountered in this situation is also greatly increased for passenger cars.

An examination of the total occupants per vehicle for the 154 vehicles involved in 145 post-crash fire collisions reveals that for vehicles in which a fatality occurred, fifty percent contained only the driver (Figure 2.2). There were 49 vehicles with fatality which burned post-crash, and 22 contained only the driver. Of the 105 vehicles that burned post-crash where no fatality occurred, 83 contained only the driver. It appears that unless this is an effect of nonreporting of occupants, the post-crash fire collisions involve an unusually high number of single occupant collisions.

An additional reflection of the high incidence of single occupants in fatal fire collisions is shown in Table 2.14. These data reveal that 17 of the total 49 vehicles contained only the driver and were single vehicle collisions.

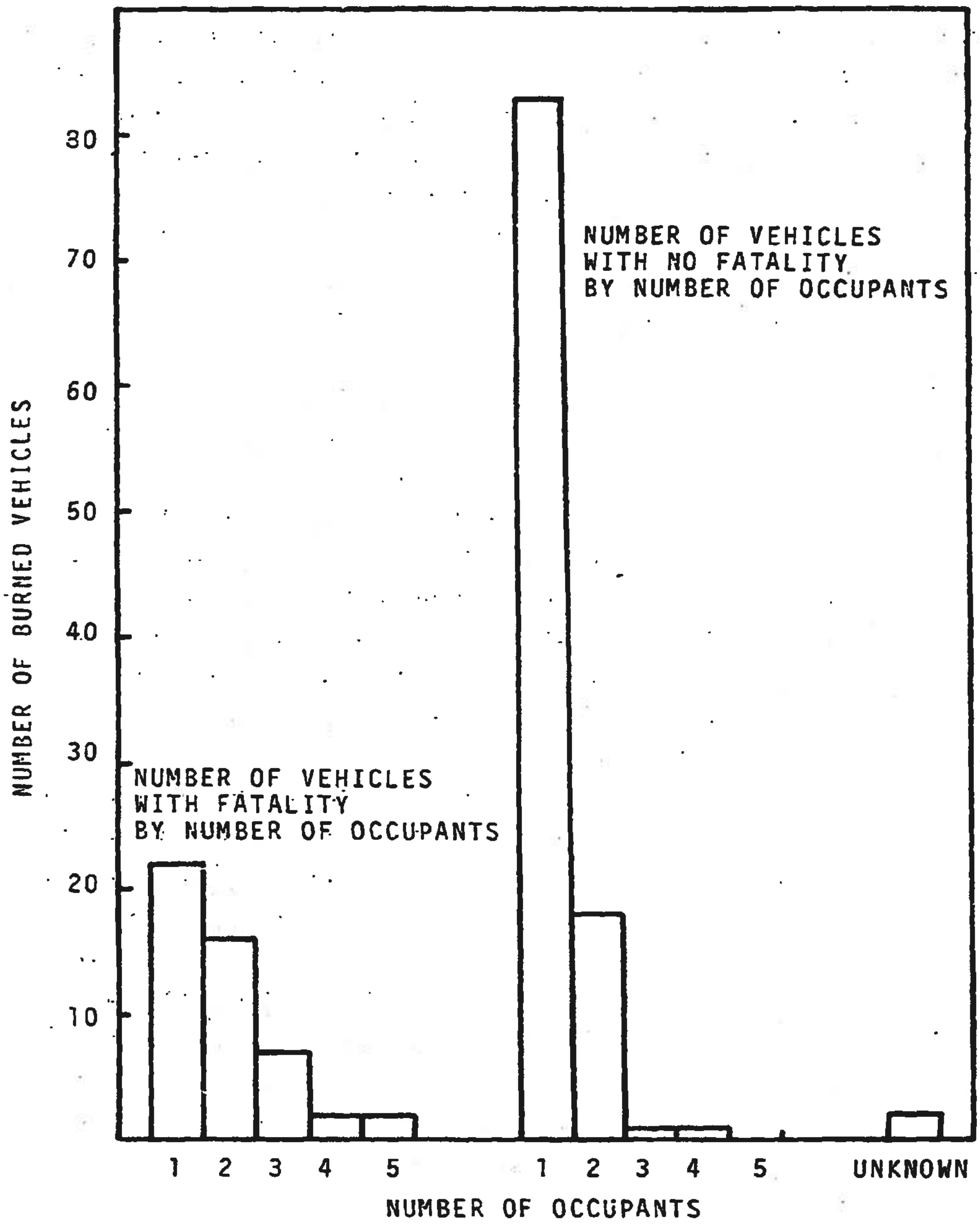


Figure 2.2. Distribution of 154 burned vehicles by number of occupants and injury severity, Oklahoma 1970 and 1971.

TABLE 2.14

DISTRIBUTION OF 49 BURNED VEHICLES WITH FATALITY BY COLLISION TYPE, NUMBER OF OCCUPANTS AND EFFECTIVE IMPACT SPEED OKLAHOMA 1970 AND 1971

Effective Impact Speed	Single Vehicle Collision						Multiple Vehicle Collision					
	Number of Occupants						Number of Occupants					
	1	2	3	4	5	6	1	2	3	4	5	6
0-9	0	0	0	0	0	0	0	0	0	0	0	0
10-19	0	1	0	0	0	0	0	0	0	0	0	0
20-29	0	0	0	0	0	0	0	0	0	0	0	0
30-39	4	0	0	0	0	0	1	0	0	0	0	0
40-49	3	1	0	0	0	0	1	2	1	0	1	0
50-59	4	1	0	0	0	0	0	2	1	0	0	0
60-69	3	1	1	0	0	0	0	0	1	1	0	0
70-79	1	1	0	0	1	0	1	0	0	0	0	0
80-89	1	0	2	0	0	0	1	1	0	0	0	0
90-99	0	0	0	0	0	0	0	1	0	0	0	0
100-109	1	0	0	0	0	0	0	4	1	1	0	0
110-119	0	0	0	0	0	0	0	0	0	0	0	0
120-129	0	0	0	0	0	0	1	0	0	0	0	0
130-139	0	0	0	0	0	0	0	1	0	0	0	0
TOTALS	17	5	3	0	1	0	5	11	4	2	1	0

Of the 154 total vehicles that burned post-crash, 85 (55 percent) involved a single vehicle striking an object or running off the road (Table 2.15).

Accident severity data were developed in a series of tables (2.14, 2.16, 2.17) to establish estimated effective speed at impact. These data were developed utilizing the following guidelines to define speed for collision type:

1. Object and all rollovers--the estimated impact speed as stated by the investigating officer.
2. Head-on--the addition of estimated impact speeds as stated by the investigating officer.
3. Rear end--the subtraction of the impact speeds as stated by the investigating officer.

4. Side--the effective speed was estimated with the formula $c = \sqrt{a^2 + b^2}$, where
c = estimated effective impact speed
a = stated impact speed of one vehicle
b = stated impact speed of the second vehicle

TABLE 2.15

DISTRIBUTION BY NUMBER OF OCCUPANTS AND
SEVERITY FOR 154 BURNED VEHICLES
OKLAHOMA 1970 AND 1971

Number of Occupants	Number of Vehicles with Fatality		Number of Vehicles with No Fatalities	
	Single Vehicle Collision	Multiple Vehicle Collision	Single Vehicle Collision	Multiple Vehicle Collision
1	17	5	47	36
2	5	11	8	10
3	3	4	1	0
4	0	2	1	0
5	1	1	0	0
6	0	0	0	0
Unknown	0	0	2	0
TOTAL	26	23	59	46

It was recognized that these estimated effective impact speeds were only gross estimates, but since the investigating officers' estimates are only gross in nature and other data were not available, it was felt that some benefit could be gained from making such computations.

Data in Table 2.16 reveal that the bulk of the post-crash fires occur at effective impact speeds in the range from 40 to 70 mph.

The distribution of the 154 burned vehicles by primary impact vector shows that the effective impact speeds for front end impact are distributed from less than 10 mph to in

TABLE 2.16

TYPE OF COLLISION BY SEVERITY AND EFFECTIVE IMPACT SPEED FOR 154 BURNED VEHICLES OKLAHOMA 1970 AND 1971

Effective Speed at Impact	Vehicles with Fatality			Vehicles with No Fatality		
	Single Vehicle Collision	Multiple Vehicle Collision	Total	Single Vehicle Collision	Multiple Vehicle Collision	Total
0-9	0	0	0	0	4	4
10-19	1	0	1	4	4	8
20-29	0	0	0	8	3	11
30-39	4	1	5	6	1	7
40-49	4	5	9	11	7	18
50-59	5	3	8	16	10	26
60-69	5	2	7	6	6	12
70-79	3	1	4	4	4	8
80-89	3	2	5	1	2	3
90-99	0	1	1	1	4	5
100-109	1	6	7	0	0	0
110-119	0	0	0	0	0	0
120-129	0	1	1	0	0	0
130-139	0	1	1	0	1	1
Unknown	0	0	0	2	0	2
TOTAL	26	23	49	59	46	105

excess of 130 mph. The distribution for rear end, side impact and rollovers is at significantly lower impact speeds (Table 2.17).

Approximately 30 percent of the total burned vehicles studied were rollovers (Table 2.18). However, half of the vehicles with fatality were involved in rollover. Whether rollovers produce half the fatalities in all collisions or only in fire collisions is not known. Unfortunately, state or national data on rollovers are not available for analysis of the implications of such findings.

There appears to be no difference in the occurrence of fatality or survival when the number of vehicle doors (pre-crash) is considered (Table 2.19). The number of vehicles with fatality or no fatality are proportionate for 1, 2, 4 or 5 doors.

Table 2.20 lists the 49 burned vehicles in which a fatality occurred by model year, vehicle type, type of impact, effective speed at impact and number of fatalities and survivors in the vehicle.

TABLE 2.17

PRIMARY IMPACT VECTOR FOR 154 BURNED VEHICLES
BY EFFECTIVE IMPACT SPEED
OKLAHOMA 1970 AND 1971

Effective Speed mph	Rear end	Front end	Side	Rollover	Rollover After Striking* Object
0-9	2	1	1	0	0
10-19	2	4	0	1	2
20-29	1	6	1	2	1
30-39	0	2	2**	2	6
40-49	3	12	5	3	4
50-59	3	15	4	5	7
60-69	0	10	4	1	4
70-79	0	7	0	3	2
80-89	0	4	0	1	3
90-99	0	5	1	0	0
100-109	1	6	0	0	0
110-119	0	0	0	0	0
120-129	0	1	0	0	0
130-139	0	2	0	0	0
Unknown	0	2	0	0	0
TOTAL	12	77	18	18	29

*Objects struck include guard rails, bridge railings, signs, etc.

**Two vehicles impacted in side by train.

TABLE 2.18

PRIMARY IMPACT VECTOR FOR 154 BURNED VEHICLES BY COLLISION SEVERITY OKLAHOMA 1970 AND 1971

Collision Severity	Rear end	Front end	Side	Rollover	Rollover After Striking Object
Fatality in Burned Vehicle	4	21	8	6	10
No Fatality in Burned Vehicle	8	56	10	12	19
TOTAL VEHICLES	12	77	18	18	29

TABLE 2.19

NUMBER OF DOORS AVAILABLE (PRE-CRASH) FOR 154 BURNED VEHICLES OKLAHOMA 1970 AND 1971

Collision Severity	Number of Doors				
	1	2	3	4	5
Fatality in Vehicle	1	31	0	14	3
No Fatality in Vehicle	0	74	0	29	2
TOTAL	1	105	0	43	5

TABLE 2.20

LISTING OF 49 VEHICLES IN WHICH A FATALITY OCCURRED

	Vehicle	Type of Impact	Effective Speed at Impact	Number of Fatalities	Number of Survivors
1.	1967 Chevrolet, 2 dr. hardtop	rollover	70	2	3
2.	1958 International pickup	rollover	50	1	1
3.	1968 Chevrolet pickup	guard rail & r.o.	75	1	1
4.	1966 Chevy II, 2 dr.	frontend	40	1	1
5.	1962 Chevrolet pickup	frontend	50	1	0
6.	1969 Ford Maverick, 2 dr.	side-train	30	1	0
7.	1966 Chevrolet, 2 dr.	side	50	1	1
8.	1959 Chevrolet, 4 dr hardtop	guard rail & r.o.	70	1	0
9.	1962 Rambler, 4 dr. wagon	side	60	4	0
10.	1966 International, 2 ton	rollover	50	1	0
11.	1961 Chevrolet, 4 dr. sedan	guard rail & r.o.	65	2	1
12.	1967 Volkswagen, 2 dr. sedan	side	60	3	0
13.	1969 White, semi-trailer	frontend	55	1	1
14.	1969 Dodge, 4 dr. sedan	frontend	105	1	1
15.	1965 White, semi-trailer	guard rail & r.o.	50	1	0
16.	1965 Ford pickup	guard rail & r.o.	30	1	0
17.	1965 Chrysler, 4 dr. sedan	side-train	30	1	0
18.	1970 Dodge Charger, 2 dr.	frontend	100	1	0
19.	1963 Pontiac, 4 dr. sedan	side	40	2	0
20.	1965 Ford, 4 dr. sedan	frontend	85	2	1
21.	1970 Ford pickup	frontend	70	1	0
22.	1967 GMC pickup	frontend	130	2	0
23.	1960 Ford Falcon, 2 dr.	frontend	45	2	0
24.	1962 Chrysler, 4 dr. sedan	rollover	80	1	0
25.	1964 Chevrolet, 2 dr. hardtop	rearend	50	2	1

TABLE 2.20--Continued.

	Vehicle	Type of Impact	Effective Speed at Impact	Number of Fatalities	Number of Survivors
26.	1969 Ford Mustang, 2 dr.	frontend	100	2	1
27.	1965 Chevrolet, 4 dr.	rollover	30	1	0
28.	1957 Chevrolet, 4 dr.	frontend	40	1	0
29.	1963 Rambler wagon, 4 dr.	frontend	105	2	0
30.	1969 White, semi-trailer	rollover	30	1	0
31.	1961 Ford, 2 dr. sedan	side	40	1	4
32.	1970 International semi-trailer	grd rail & r.o.	60	1	0
33.	1962 Cadillac, 2 dr.	frontend	105	1	1
34.	1971 Winnebago motor home	frontend	105	1	3
35.	1970 Chevrolet pickup	frontend	70	1	0
36.	1966 Ford, 4 dr.	frontend	85	1	0
37.	1966 Mercury wagon, 4 dr.	frontend	125	1	0
38.	1957 Chevrolet pickup	guard rail & r.o.	50	1	0
39.	1971 GMC pickup	bridge abut. & r.o.	65	1	0
40.	1969 Chevrolet pickup	guard rail & r.o.	10	2	0
41.	1968 Chevrolet pickup	rearend	40	1	0
42.	1970 Ford Pinto, 2 dr.	frontend	80	2	1
43.	1970 Plymouth Valiant, 4 dr.	frontend	80	1	1
44.	1961 Ford pickup	frontend	60	1	0
45.	1972 Chevrolet pickup	frontend	95	1	1
46.	1961 Chevrolet, 4 dr. sedan	side	40	1	1
47.	1964 Ford pickup	guard rail & r.o.	40	1	0
48.	1969 Chevrolet, 4 dr. sedan	frontend	105	1	1
49.	1965 Mercury, 4 dr. sedan	frontend	40	2	1

2.2.5 Data Collection in Kansas

The data collection system for the state of Kansas was instituted late in 1970. The Kansas Highway Commission agreed to screen the narrative section of accident reports as they were received during calendar year 1971 for post-crash fire and submergence accidents. In addition, a retrospective search of the files was conducted for calendar year 1970. The 1970 data consisted primarily of fatal collisions and are not complete for all post-crash fire or submergence accidents. The other source of Kansas data for this two year period was death certificates for fatally injured occupants of vehicles that burned or submerged post-crash.

Accident reports involving fire or submergence were duplicated and copies were supplied routinely by the Kansas Highway Commission. These reports were the basis of reporting from this state.

It was not possible to obtain a routine screening procedure for death certificates; therefore, no double information source was available to improve reporting accuracy. Death certificates were obtained quarterly by submitting a list of victims (from the accident reports) to the Kansas State Board of Health. Death certificates were obtained on victims that were fatally injured in vehicles that burned or submerged.

2.2.6 Analysis of Kansas Post-Crash Fire Data

During calendar years 1970 and 1971, 66 post-crash fire accidents were retrieved (Table 2.21). For this period, there were 104,014 non-pedestrian motor vehicle accidents reported in Kansas (excludes pedestrians, motorcycle, motorbike and animal). The low number of post-crash fire accidents reported is partially due to the fact that no non-fatal accidents of this type were reported during 1970 and few were reported during 1971. Additionally, Kansas had no special requirement or method for reporting collision fires. For fatal collisions, reporting of fires appears to be fairly reliable, based upon the similarity of Oklahoma and Kansas experience (4.7 percent versus 4.9 percent of all non-pedestrian fatal accidents involved fire). Because of these limitations of the reporting system in Kansas, the bulk of the data reported here is on fatal collisions.

TABLE 2.21

MOTOR VEHICLE COLLISIONS INVOLVING POST-CRASH FIRE
KANSAS 1970 AND 1971

	Number of Accidents	Fatal-ities	Percent of all Fatal.	Injuries	Not Injured in Burned Vehicle
All Accidents* State Total	104,014	1224	100	2243	NA
Post-Crash Fire	66	59	4.9	56	18

*Non-pedestrian accidents. Also excludes motorcycle, motorbike, etc.

Fifty-nine (59) fatalities or 4.9 percent of the total 1,224 non-pedestrian fatalities for 1970 and 1971 resulted from collisions where the victim was the occupant of a vehicle that burned post-crash.

The fatality rate in vehicles that burn is similar to the experience in Oklahoma. While 104,014 accidents produced 1,224 fatalities and 2,243 injuries, 66 post-crash fire collisions produced 59 fatalities and 56 injuries in the burned vehicle. Again, each post-crash fire produces almost one fatality. For all non-pedestrian accidents, about one fatality per 84 accidents is produced in Kansas, which is similar to Oklahoma experience. Since reporting is not complete for non-fatal post-crash fire accidents in Kansas, the injury ratio cannot be established as reliable, as was the case in Oklahoma.

The distribution of post-crash fire collisions by injury severity is skewed toward fatal accidents and is a reflection of the reporting of only fatal collisions during the first year of the two year reporting period (Table 2.22).

TABLE 2.22

DISTRIBUTION OF POST-CRASH FIRE COLLISIONS BY INJURY SEVERITY KANSAS 1970 AND 1971

Collisions with Fatality in Burned Car	Collisions with Injury in Burned Car	Collisions with No Injury in Burned Car	Total Collisions
39	15	12	66

The death certificates for the 59 fatalities associated with post-crash fires were acquired and examined for principal or contributing cause of death (Table 2.23).

TABLE 2.23

DISTRIBUTION OF 59 FATALITIES BY INJURY SITE FOR COLLISIONS INVOLVING POST-CRASH FIRE* KANSAS 1970 AND 1971

Total Fatalities	Fatal Injuries			
	Head	Internal	Head Plus Other	Burns
59	8	17	3	31

*Source: Death certificates.

Even if only those who were listed as death by burns are considered, they represent 2.5 percent of the total non-pedestrian fatalities in Kansas for this period of two years.

Injury information on Kansas accident reports is currently not sufficient for an adequate determination of the distribution of non-fatal injuries. This deficiency has been found to be common to accident reports from several of the states.

The age distribution of drivers and passengers killed in post-crash fire accidents appears in Table 2.24. No age effect is apparent, since approximately equal numbers of occupants above and below 44 years of age were killed.

TABLE 2.24

DRIVERS AND PASSENGERS KILLED IN VEHICLES THAT BURNED POST-CRASH, DISTRIBUTION BY AGE AND SEX
KANSAS 1970 AND 1971

Age Group	Drivers Killed		Passengers Killed	
	Male	Female	Male	Female
0-4	0	0	0	0
5-13	0	0	4	0
14-15	0	0	2	0
16	0	0	1	0
17-21	7	0	6	2
22-27	2	3	2	1
28-33	4	0	0	0
34-39	2	0	0	1
40-44	1	0	0	0
45-54	6	0	1	1
55-64	5	0	0	0
65-74	3	0	1	1
75+	1	1	0	0
TOTAL	31	4	17	7

Location of occupants in vehicles is not available for all Kansas accidents nor is this information complete for those involving post-crash fire (Table 2.25). Position of vehicle occupant is not routinely reported in Kansas.

TABLE 2.25

DISTRIBUTION OF REPORTED OCCUPANTS BY INJURY SEVERITY AND POSITION IN VEHICLE--POST-CRASH FIRE KANSAS 1970 AND 1971

Occupants	Left Front	Center Front	Right Front	Left Rear	Center Rear	Right Rear	Not Stated	Total
Post-crash Fire								
Killed	35	0	7	1	1	0	15	59
Injured	24	2	6	1	0	3	20	56
No Inj.	11	1	1	1	1	0	1	16

Few injured or non-injured occupants are listed on accident reports and in most cases only the drivers and fatally injured occupants are listed.

The distribution of total post-crash fire accidents by rural and urban locations reveals an experience similar to Oklahoma's (Table 2.26). Of the 42 total fatal collisions, 32 (76 percent) occurred in rural locations. Eighty-eight (88) percent of the non-fatal collisions occurred in rural areas, which is similar to Oklahoma's experience.

Again comparing with national experience, where two fatal accidents occur in rural areas for each fatal collision in urban areas, post-crash fire fatality is over-represented as a rural phenomenon. A monthly distribution is presented in Table 2.27.

Vehicle registration by manufacturer was also not available for Kansas, so specific comments about the post-crash fire problem by vehicle make is not possible. Passenger cars that burned totaled 48 during 1970 and 1971 in Kansas

TABLE 2.26

TIME AND LOCATION DISTRIBUTION FOR 66 POST-CRASH FIRE COLLISIONS KANSAS 1970 AND 1971

Time	Rural		Urban		Total	
	Fatal	Non-Fatal	Fatal	Non-Fatal	Fatal	Non-Fatal
6:00-7:59 AM	2	1	0	0	2	1
8:00-9:59 AM	2	0	1	1	3	1
10:00-11:59 AM	4	0	0	0	4	0
12:00-1:59 PM	3	0	2	0	5	0
2:00-3:59 PM	1	1	0	0	1	1
4:00-5:59 PM	4	2	3	0	7	1
6:00-7:59 PM	2	0	0	0	2	0
8:00-9:59 PM	2	7	2	0	4	7
10:00-11:59 PM	4	3	0	1	4	4
12:00-1:59 AM	3	3	1	0	4	3
2:00-3:59 AM	2	2	0	1	2	3
4:00-5:59 AM	3	2	1	0	4	2
TOTAL	32	21	10	3	42	24

(Table 2.28). By manufacturer they included: General Motors, 24; Ford, 10; Chrysler, 12; American Motors, 1; and Volkswagen, 1. Five of the burned vehicles were pickups (Table 2.29). Large commercial trucks accounted for 22 of the total 75 vehicles that burned post-crash (Table 2.30).

The distribution of burned vehicles by model years reveals that over 45 percent of the vehicles that burned post-crash in Kansas during 1970 and 1971 were 1968 models or newer (Table 2.31). In this state as in Oklahoma, there appears to be an unusually high involvement of newer vehicles in collisions where fire occurs after the crash.

Vehicles that burned after the crash in the 66 collisions came to rest on their side or top 16 percent of the time (Table 2.32). However, a determination of final resting position was not possible in an equal number of cases, so it is difficult to draw any definite conclusion from this statistic.

TABLE 2.27

DISTRIBUTION OF 66 POST-CRASH FIRE COLLISIONS BY LOCATION AND MONTH KANSAS 1970 AND 1971

Month	Rural		Urban		Total	
	Fatal	Non-Fatal	Fatal	Non-Fatal	Fatal	Non-Fatal
January	0	2	0	0	0	2
February	1	1	2	0	3	1
March	1	1	0	0	1	1
April	3	1	1	1	4	2
May	3	6	1	0	4	6
June	3	1	1	1	4	2
July	3	2	1	1	4	3
August	10	1	0	0	10	1
September	2	3	2	0	4	3
October	1	0	1	0	2	0
November	3	1	1	0	4	1
December	2	2	0	0	2	2
TOTAL	32	21	10	3	42	24

TABLE 2.28

PASSENGER CARS THAT BURNED POST-CRASH DISTRIBUTION BY MANUFACTURER KANSAS 1970 AND 1971

	American Motors	General Motors	Ford Motor Co.	Chrysler Corp.	Volks-wagen	Total
Fatality Inside	1	7	10	10	1	29
No Fatality Inside	0	17	0	2	0	19
TOTAL	1	24	10	12	1	48

TABLE 2.29

PICKUP TRUCKS THAT BURNED POST-CRASH DISTRIBUTION BY MANUFACTURER KANSAS 1970 AND 1971

	General Motors	Ford Motor Co.	Chrysler Corp.	Intrntl Harvester	Total
Fatality Inside	1	1	0	1	3
No Fatality Inside	0	0	1	1	2
TOTAL	1	1	1	2	5

TABLE 2.30

COMMERCIAL TRUCKS THAT BURNED POST-CRASH DISTRIBUTION BY MANUFACTURER KANSAS 1970 AND 1971

	Ken-worth	Intntl Hrvstr	White	Ford	GMC	Peter-built	Total
Fatality Inside	0	2	2	1	7	2	14
No Fatality Inside	1	5	0	1	0	1	8
TOTAL	1	7	2	2	7	3	22

TABLE 2.31

VEHICLES THAT BURNED POST-CRASH DISTRIBUTION BY MODEL YEAR KANSAS 1970 AND 1971

	1971	1970	1969	1968	1967	1966	1965	1964	1963 & Older	Total
Pass. Car	3	9	5	3	4	3	5	4	12	48
Pickup	0	0	2	0	2	0	0	0	1	5
Com. Truck	2	1	7	2	3	1	0	1	5	22
TOTAL	5	10	14	5	9	4	5	5	18	75

TABLE 2.32

RELATIONSHIP OF INJURY SEVERITY TO FINAL VEHICLE POSITION FOR 66 POST-CRASH FIRE COLLISIONS INVOLVING 75 VEHICLES KANSAS 1970 AND 1971

	Number of Vehicles	Fatal Injury	Injury	No Injury
Vehicle Upright	53	38	46	11
Vehicle on Side or Top	12	13	3	0
Unknown	10	8	7	7
TOTAL	75	59	56	18

It is interesting to note that 13 of the 59 fatalities (22 percent) occurred in these vehicles, but that only 3 (5 per cent) of the injuries occurred in them. The comparable Oklahome percentages were 27 percent of fatals and <u>30 percent</u> of injuries. Referring to the Oklahoma experience where information is more complete, one might assume that many of those unknown positions might fall into the category of vehicles that came to rest on their side or top.

Of the 66 post-crash fire collisions, 39 (59 percent) involved a single vehicle striking an object or running off the road (Table 2.33).

TABLE 2.33

SINGLE AND MULTIPLE VEHICLE COLLISIONS (POST-CRASH FIRE) BY INJURY SEVERITY FOR 66 COLLISIONS KANSAS 1970 AND 1971

Type of Collision	Fatal Collision	Non-Fatal Collision	Total
Single Vehicle	20	19	39
Multiple Vehicle	19	8	27
TOTAL	39	27	66

2.2.7 Oklahoma and Kansas Submergence Data

The original survey of fifty states and the District of Columbia was designed to determine the availability of submergence data as well as post-crash fire information. It was felt that vehicle submergence also represented one of the most serious escape worthiness situations that was identifiable. Ultimately, only two states, Oklahoma and Kansas, participated fully in the effort to acquire data on submergence of motor vehicles.

The information systems in both states were identical to those designed for the collection of post-crash fire information. In Oklahoma information was acquired from accident reports, death certificates, newspaper clipping service and in-depth evaluation of selected cases. In Kansas accident reports were screened and provided routinely and death certificates for those fatally injured were acquired.

Submergence data was collected for two years in both states (1970 and 1971); however, information from Kansas is not included since only fatal submergence collisions were reported for 1970 and reporting was incomplete for 1971.

It was not possible to determine whether all of the cases included in this report actually involved vehicles that were totally or partially submerged since water depth was not reported. The accident reports were screened in both states for vehicles that came to rest in a river, creek, lake, pond or other body of water. It is possible that some such bodies of water were actually almost dry when the accident occurred, since many small streams do not contain much water during the summer months. A review of the newspaper clippings for Oklahoma indicates that almost all vehicles were in water of great enough depth for drowning to occur. The in-depth evaluation of a number of cases also indicated that there was actual submergence of the vehicle. In addition, over one-third of the fatalities in Oklahoma from this sample were listed as death by drowning on the death certificate. Even though the submergence data presented are not greatly reliable from the standpoint of water depth, the majority of vehicles were indeed submerged in water of sufficient depth to cause death by drowning if escape or rescue did not occur.

2.2.8 Analysis of Oklahoma Submergence Data

During calendar years 1970 and 1971 there were 98 vehicle submergences in the state of Oklahoma. There were 31 fatalities in the 98 vehicles which represented 2.2 percent of all non-pedestrian fatalities during this period. An additional 76 individuals received injuries in such accidents and 45 were reported as not injured (Table 2.34).

TABLE 2.34

MOTOR VEHICLE SUBMERGENCE
OKLAHOMA 1970 AND 1971

	Number of Accidents	Fatalities	Percent of all Fatal.	Injured	Not Injured
All accidents* State total	129,366	1391	100.0	37,554	NA
Submergence	98	31	2.2	76	45

*Non-pedestrian accidents. Also excludes motorcycles, motorbikes, etc.

It is again clear that all not-injured occupants are not listed on accident reports.

It is difficult to assess the total importance of submergence in terms of loss of human life and injury due to the brevity of existing reporting systems. Twelve (12) of the 31 persons killed in these accidents drowned (Table 2.35).

These 12 drowning victims amount to 0.8 percent of all non-pedestrian fatalities in Oklahoma during 1970 and 1971.

TABLE 2.35

DISTRIBUTION OF 31 FATALITIES BY CAUSE OF DEATH*
FOR COLLISIONS INVOLVING SUBMERGENCE
OKLAHOMA 1970 AND 1971

Total Fatalities	Death Caused by Impact Injuries	Death Caused by Drowning
31	19	12

*Source: Death certificates.

2.2.9 Escape Worthiness Survival Indices

Escape worthiness information was found not to be available routinely from existing sources other than for general information related to post-crash fire and submergence. Reporting that fire or submergence occurred is reliable only in Oklahoma. Accident reports, death certificates and newspaper clippings have provided some overview of the general problems associated with egress from a burning or submerging vehicle subsequent to a crash; however, data related to specific hazards which inhibit escape must be acquired by other means.

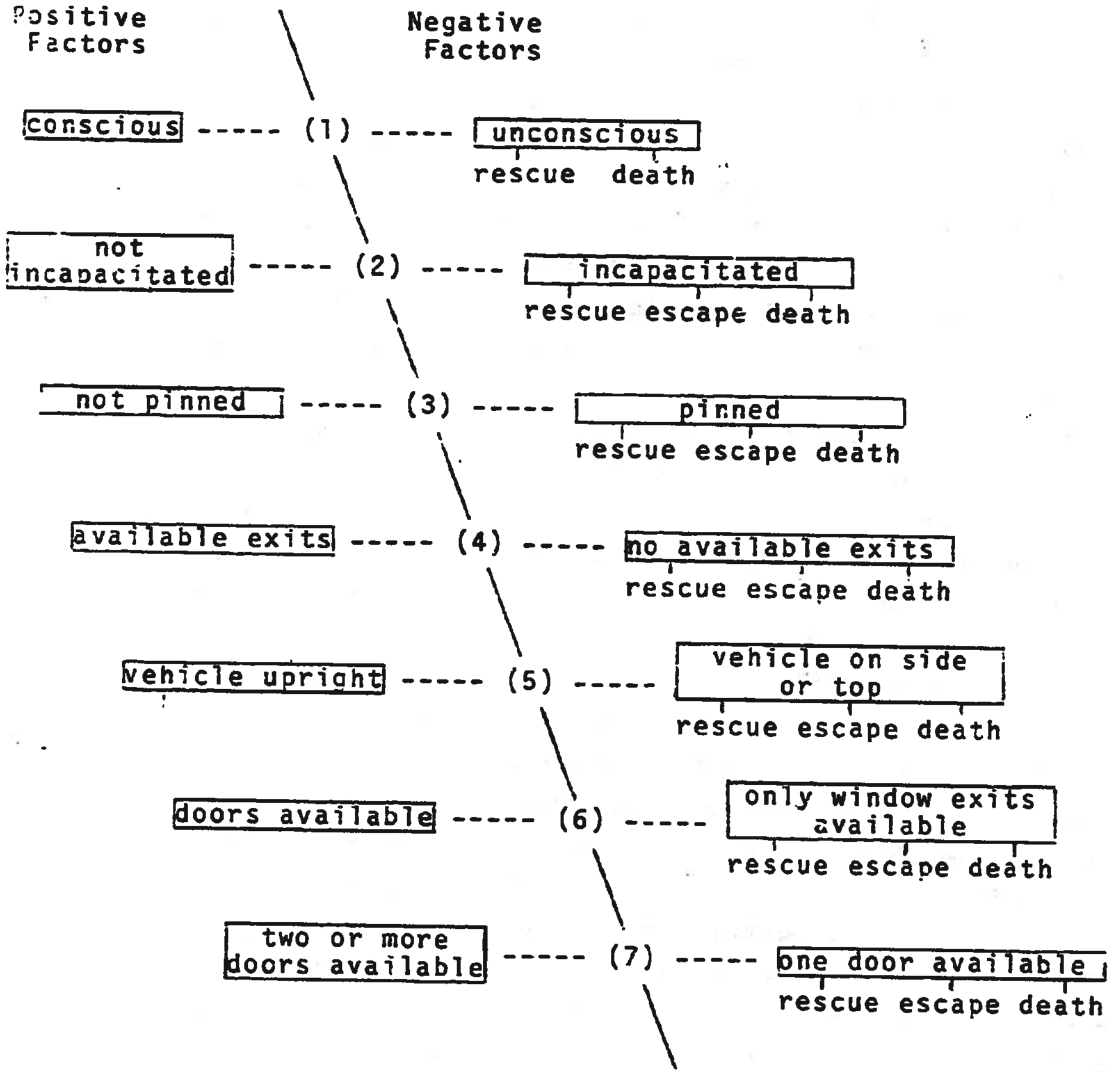
Special evaluation of a few fire or submergence crashes in Oklahoma has provided some hypotheses that may provide the specific data required for evaluation of escape worthiness parameters. It appears that the most logical approach for validating these hypotheses is collection and analysis of specific escape worthiness information from the investigations done by the Multidisciplinary Accident Investigation Teams and other in-depth investigations. The epidemiological model that follows (Figure 2.3) could be used by MDAI Teams to provide much needed data in this area. This model is based on the findings of the data collection programs in Oklahoma and Kansas and on the special evaluations conducted by the staff.

These Escape Worthiness Survival Indices (Figure 2.3) represent a summary of the major findings. The crashes considered were those in which fire or submergence occurred after impact. Since the bulk of the cases investigated involved serious injury or death, the model is skewed toward more severe cases. This type of case was considered more fruitful for evaluation because they receive more careful police investigation and because the spectacular collisions receive more coverage, both textual and photographic, in the media.

The indices represent an attempt to rate in order of importance the conditions which prevent the survival of occupants in vehicles that burn or submerge post-crash. Rather than attempt to include all factors, this sequence includes only the most severe conditions which have continuously occurred in both single and multiple vehicle collisions where the vehicle burned or submerged.

Based on actual evaluations, it was concluded that death is probable for vehicle occupants in any one of Negative Situations 1 through 5 when a fuel-fed fire is present or the vehicle runs into water of five or more feet deep (Figure 2.3). The only probable method of escape is rescue in the first four negative situations. In all situations, time is of the essence. The only additional potential for survival is escape in Negative Situation 5, where the vehicle is on its side or top. If the vehicle is on the side, it is very unlikely that escape will occur without assistance. Limiting factors include the weight of the door, the distance the subject must reach in order to disengage the latch and the difficulty encountered in climbing this distance. If the

ESCAPE WORTHINESS SURVIVAL INDICES



NOTE: If all seven positive factors are present, unassisted escape is probable. The seven negative factors are in descending order of priority. Any one of the negative factors presents a potential for death in fire or submergence collisions.

Figure 2.3. Escape worthiness survival indices.

vehicle comes to rest on the top, the primary limiting factors are the temporary disorientation of the occupant(s), roof crush, seat belts and especially jamming of doors. The disorientation problem is more severe in darkness.

Rescue is questionable in the preceding situations since many collisions of this severity occur in rural areas and/or at night. Based on limited data it is felt that if rescue is not effected within about three minutes post-crash, it is either too late to save the occupant(s) or the fire is too intense to approach the vehicle. In the case of submergence, there is probably more time available to the occupant(s).

Death is possible in both Negative Situation 6 and 7. At the impact level required for jamming of all doors, it appears that occupants do not use windows for exits in most cases even when only partially disoriented. The tendency is toward struggling with the jammed doors rather than rolling down windows or breaking the windshield and effecting escape through the window openings. Escape in Negative Situation 6 depends primarily on rescue or in some cases on the side window adjacent to the occupant being down at impact.

The possibility of escape increases in Negative Situation 7 but is dependent upon location of the available door. That is to say, if the unjammed door is near the fire source it is also possible that escape will not occur.

Even though the pattern of escape and <u>probable survival</u> is not totally clear some general hypotheses can be formulated from limited experience to date. If the occupant is conscious, not incapacitated, not trapped by vehicular components, has exits available and if the vehicle is upright with two or more doors unjammed, unassisted escape is highly probable in the post-crash fire collision.

The potential for escape from a "submerging" vehicle closely parallels that for post-crash fire except that rescue is less likely for all seven critical indices and escape is also more limited for the same indices.

Escape worthiness aspects of less hazardous environments (no fire or submergence) are not totally clear but some general observations are in order. The primary difference is that time is not so critical a factor for survival. Since an immediate threat of death is not presented by fire or water, the probability of rescue is assured when other individuals are present within a reasonable time span. Occupants pinned by vehicular components (Negative Situation 3) remain a serious problem since seldom is proper equipment available for extrication of victims. It appears that the degree of injury and potential for death increases with time due to the inadequacy of emergency medical services currently available.

2.2.10 Conclusions and Recommendations

Based upon the preceding analysis of accident information and the special investigations detailed in Appendix B in the second volume of this report, the following conclusions are advanced.

1. Post-Crash Fire: A review of post-crash fire experience for motor vehicles in the states of Oklahoma and Kansas over a two year period makes it clear that although the frequency of occurrence of post-crash fire collisions is low, the number of fatalities associated with this type of collision is proportionally quite high. Fatalities which occur in vehicles that burn involved 4.7 percent of the total non-pedestrian fatalities in Oklahoma and 4.9 percent in the state of Kansas.
2. Those cases currently listed as death by burns or incineration on the death certificates amount to 3.3 percent of the total non-pedestrian fatalities in Oklahoma and 2.5 percent in Kansas.
3. The post-crash fire environment is obviously very severe. While one fatality is produced for every 93 accidents for non-pedestrian accidents, the post-crash fire accident produces one fatality for every two such accidents.

4. Based on the Oklahoma and Kansas experience, post-crash fire is clearly an engine-fuel problem. Of the 211 post-crash fire accidents involving 229 burned vehicles in Oklahoma and Kansas during the two year period, there is no indication that a single occurrence did not involve fuel. A limited number of in-depth evaluations of these crashes indicates that lack of fuel tank integrity is the most frequent problem.
5. It is difficult to relate the Oklahoma and Kansas fire data to the eventual effectiveness or lack of effectiveness of FMVSS 301, since speed data at impact for most of the cases studied are either not available (Kansas) or subject to some question (Oklahoma). However, sufficient evidence on barrier-equivalent speeds is available to indicate that the standard may not prevent fuel spills when more rigid constraints on fuel tank performance could do so. In many of the cases evaluated which occurred at barrier speeds exceeding those contemplated by the standard, victims were alive and attempting to escape while a fuel-fed fire was consuming the vehicle.
6. Post-crash fire collisions where a fatality occurs are clearly a rural phenomenon. About 80 percent of the collision fire fatalities occur in rural areas, while only only about 20 percent of such fatalities occur in urban areas. For all fatal collisions, about 66 percent occur in rural areas and 33 percent in urban areas. Herein lies a significant factor for future evaluation. It appears that unassisted escape is more difficult in fire collisions and that assistance is provided in many cases by passing motorists in urban areas. With no assistance, victims in rural areas are burned to death.
7. Even though statistical data are now available and fairly reliable on post-crash fire in Oklahoma and Kansas, many significant factors are not recorded or even noted. Specific information on escape times, number of doors jammed,

exit used by persons during escape, emergency medical services and numerous other factors are not a part of routine police reporting activities. Though not a portion of the original contract, numerous attempts were made to acquire such data. These activities were generally unsuccessful. Such data can best be acquired by multidisciplinary teams utilizing special report forms or by police routinely using an improved report form.

8. Insight into specific escape worthiness parameters cannot be gained by review of routine police accident reports, death certificates, or newspaper clipping services.

9. In an attempt to gain information on escape worthiness parameters, a number of in-depth evaluations were conducted by the staff (Appendix B). These reports resulted from interviews with investigating officers, survivors, witnesses, physicians, and other persons associated with a crash. In addition, the vehicle, road, weather and other conditions were described. These reports, particularly on post-crash fire collisions, provided much of the basis for the indices presented in Section 2.2.9 (Escape Worthiness Survival Indices). The in-depth evaluations provided the significant conclusion that the system of data collection for post-crash fire collisions in Oklahoma was adequate and generally provided accurate information.

10. Death by drowning in motor vehicles remains an area where pertinent data are limited. Attempts to acquire submergence accident reports from a number of states were unsuccessful. It was not possible to acquire useful data except by review of the narrative portion of accident reports, review of death certificates, and by the use of a newspaper clipping service. This method was only successful in the state of Oklahoma where the authorities took a special interest in providing data.

11. In Oklahoma, drowning was listed as the principal cause of death in 0.8 percent of the non-pedestrian fatalities during a 2-year period (1970 and 1971). During this period, 2.2 percent of the total non-pedestrian fatalities occurred in vehicles that submerged. The decision on cause of death in these occurrences is somewhat arbitrary since autopsies were not performed and it was not determined which victims were actually killed by impact injuries and which by drowning. The death certificate information represented merely a guess by the attending physician.

In any assessment of the significance of these submergence fatalities, it should be clearly remembered that in Oklahoma, opportunities for submergence are relatively rare, compared to many other states. Since the total annual rainfall is limited, fewer watercourses developed per unit of area. Those watercourses which do exist are very often dry or almost dry practically all the time. Despite the fact that Oklahoma has more manmade-lake shoreline than any other state, the lakes are scattered and intersected by few primary highways.

12. A number of in-depth case evaluations which involved interviews with escape occupants, witnesses, police investigators or others have shown that information on how to escape would be helpful to those involved in such a collision. Surface escape through windows appears to be the only satisfactory method of escape. With minimal vehicle damage upon impact, vehicles will remain on the surface of the water for approximately 2 to 5 minutes. This time is ample for a very healthy, agile, non-injured occupant to egress through the side window. However, for those who are injured, disabled, or very young or aged, egress may be too difficult and the time too short.

13. If an individual remains in a vehicle until it is totally submerged, there is little chance for survival. There are several assumptions (based on a limited number of cases) that make this outcome probable. With the current vehicle roof designs there is probably no entrapped air bubble. Even is a small air bubble does exist, it would not be adequate for or very accessible to the occupant(s). Additionally, the test vehicle used during submergence tests under Contract FH-11-7303 experienced roof crush from the water pressure which reduced the depth of a potential air pocket. An additional factor experienced during these tests was jamming of doors due to stresses on the vehicle body.

Based upon the data analysis and conclusions, the following are recommended:

1. Fuel tank integrity is the most critical problem in post-crash fire collisions. Individuals are surviving the initial crash only to burn to death in the vehicle. Therefore, it is recommended that steps be taken to prevent the spillage of fuel during and subsequent to a crash.

   Since pickup trucks appear to represent a greater fire problem than passenger cars, it is recommended that the fuel tanks in pickup trucks be removed to a less hazardous location.

2. It is not possible to draw concrete conclusions about specific problems related to the motor vehicle fire problem on a national basis due to the inadequacy of national statistics. NHTSA should collect data on a first hand basis from the states and such data should be more comprehensive in scope and provide more pertinent information about collisions. Data collection procedures should provide information about all occupants in motor vehicle collisions in order that exposure data can be developed.

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CHAPTER THREE

ESCAPE WORTHINESS STUDIES

The introductory statements presented in the report for Contract FH-11-7303 established several facts concerning the concept of escape worthiness and its evaluation as a factor in the post-crash phase of an accident. These facts are summarized below because of their continuing relevance to the current research program.

1. Continuing progress in the pre-crash and crash aspects of motor vehicle safety should be accompanied by a comparable improvement in post-crash safety if the greatest benefits from efforts in the two former areas are to be realized.
2. The relationships between causal factors and injuries resulting from motor vehicle accidents are probably more difficult to establish in the post-crash, escape worthiness area as compared to the pre-crash and crash areas.
3. Accident data which can be used to establish the causal relationship between a given post-crash escape worthiness environment and injuries which result from escape worthiness problems are very difficult to obtain because of their transient nature and/or the lack of concern by responsible authorities for reporting such data.

The research performed under Contract FH-11-7303 resulted in a preliminary analysis of the major problems of escape worthiness, and through some pilot studies, experimental methodologies were developed for studying these problem areas further. These experimental methodologies have been developed further during this research effort and data has been gathered which can be used in support of rules-making activities of NHTSA.

This current research effort has been organized in a similar manner to the research performed under Contract FH-11-7303, where three distinct areas of research were recognized:

1. Post-crash egress from a passenger car on land.
2. Vehicle entry dynamics, floating time, and post-crash egress when a passenger car submerges in water.
3. Post-crash egress from school buses and intercity buses on land.

The major emphasis of this research effort for passenger cars on land was the development of a predictive model for evaluating the escape time from a passenger car, using a specified set of vehicle dimensions. In addition to evaluating escape time for a number of post-crash conditions, an evaluation of vehicle equipment such as seat belts, door latches and door locks was made as related to escape worthiness. This research is described in Section 3.1.

Research in the area of passenger car submergence was directed toward the analytical description of vehicle entry dynamics and the prediction of vehicle floating times when one enters the water. It was necessary to develop measurement techniques for evaluating vehicle leak rate when submerged and vehicle interior volume in order to predict floating time. This research is described in Section 3.2 and Appendixes C.1 through C.4.

Research in the area of bus escape worthiness was performed in three phases. Escape times were evaluated for various conditions of escape from school buses and intercity buses. This research indicated the need to perform strength measurements of passengers for operating bus emergency exit latching mechanisms, which was the next phase of the research program. Finally, an attempt was made to identify and evaluate other parameters of escape worthiness as related to the design and operation of bus emergency exits. Sections 3.3, 3.4 and 3.5 describe these phases of the research related to bus escape worthiness.

3.1 ESCAPE WORTHINESS--PASSENGER CARS ON LAND

3.1.1 Philosophy of the Research

The concept of escape worthiness which has been defined in the report for Contract FH-11-7303 (1) implies that any research program directed to investigate this area include a study of the parameters related to accomplishing the following objective: "To preserve the motor vehicle occupants from further harm after a collision by providing safe and easy egress from the vehicle."

The number of parameters which can influence the attainment of this objective is large, dictating that the research program be directed toward studying only the more important parameters. Of the parameters related to the vehicle, those involving certain design parameters and the materials of construction were judged most important in studying escape worthiness. While there are definitely some vehicle similarities as related to design and materials of construction, there are obviously a great many differences in vehicle design which must be taken into account in any research program by the choice of parameters to be investigated. It is apparent that vehicle size and shape parameters rather than make-model-year parameters should be considered and should somehow be related to escape worthiness. This approach would hopefully permit the data to be used in some sort of predictive mathematical model. That is, the escape worthiness data, utilizing a small number of automobiles, collected during the experimental phase of this project should ultimately be related to design parameters (selected dimensions of the vehicle) rather than to the vehicle tested per se (e.g., a 1969 Toronado 2-door hardtop).

Similarly, users of passenger cars differ greatly in physical characteristics such as height, weight and age. The preliminary escape worthiness studies performed under Contract FH-11-7303 indicated that some subject parameters (age, sex, size, physical condition as a result of the accident, etc.) are of definite importance in effecting escape from an automobile. Therefore, subject parameters as well as vehicle design parameters must be considered in any escape worthiness study.

The problem of passenger car egress under emergency conditions is of ultimate interest in this study. This study itself, however, could not capture the flavor of a true emergency egress situation which follows a collision. To compensate for a true emergency egress situation in the test program, it was necessary to make an appropriate and judicious selection from among the many factors, human, vehicle, and environmental, which affect the ability of an individual to escape. The criteria embodied in the selection process constitute the general philosophy of this research effort.

One method of approach to categorizing these various factors involves the assumption that certain pre-crash parameters of the vehicle-driver (passenger) -environment system are extremely important in the post-crash escape situation. Some of these pre-crash parameters include:

1. Vehicle Characteristics
    a. Physical dimensions of the vehicle interior
    b. Size and shape of door and window openings
    c. Passenger restraint system
    d. Position and type of door handles, window cranks, door lock buttons, seat back latches, etc.
    e. Integrity of passenger compartment construction
2. Passenger Characteristics
    a. Age, sex, and physical strength
    b. Degree of familiarity with the vehicle

3. Environmental Characteristics
    a. Ambient illumination (day, dusk, night)
    b. Weather (rain, snow, etc.)

The crash phase of the accident may be considered to modify some of the above parameters so that escape in the post-crash phase is further degraded. Some modifications are:

1. Vehicle Condition
    a. Reduction in size of the passenger cabin
    b. Reduction in effective window door area
    c. Jamming of the doors and windows
    d. Orientation of the vehicle (on wheels, side, or top)
2. Passenger Condition
    a. Injury (type and severity)
    b. Shock, panic, disorientation of passengers

From the above lists of characteristics and conditions it is apparent that any controlled experiment designed to investigate escape worthiness in automobiles must be severely limited, since many of the conditions are impossible to simulate and others are prohibitively expensive.

Since a portion of this interdisciplinary effort regarding escape worthiness involved the flammability of vehicle materials, it was decided that a reasonable first approach to the problem of measuring escape worthiness could be represented by an attempt to measure escape time under almost "ideal conditions." This approach provides some insight as to the minimum times to escape under certain passenger and vehicle conditions. The numerical values of escape time are then measures of relative difficulty to escape rather than indicators of the time to escape under actual post-crash conditions. Further, if the flammability of material inside a vehicle is such that escape from that vehicle is impossible or improbable under "ideal" conditions, passengers in that vehicle are subject to a constant, unnecessary hazard. By "ideal" we mean that:

1. The vehicle is in its normal orientation with all four wheels on the road.
2. The passengers have not been subjected to a crash situation, and therefore disorientation, shock, or panic is not a factor.
3. The passengers have the benefit of practice and familiarity with the vehicle.

An experiment involving the investigation of escape worthiness under the above "ideal" conditions was designed with the following independent variables:

1. Automobiles (5 ranging in size from full size to subcompact)
2. Sex (all male, all female, mixed)
3. Age group (19-29 years, 39-59 years)
4. Available escape route (4 doors when vehicle is so equipped, 2 doors, 1 door, all windows, 2 windows, 1 window)
5. Injury simulation (1 passenger simulating unconsciousness, or no one injured)
6. Panic simulation (occurred once for each subject group and involved an explosion, smoke and fire apparently coming from the engine compartment)
7. Ambient light condition (starlight, daylight)

3.1.2 Methodology

3.1.2.1 <u>Introduction</u>: The methodology section is divided into five subsections to discuss in detail the equipment, subjects, experimental design, experimental procedure and night study considerations for this experiment.

3.1.2.2 Equipment: A total of five passenger cars were instrumented and tested for their relative degree of escape worthiness. These vehicles were the following:

1. 1969 Oldsmobile Toronado (2 door hardtop)
2. 1967 Ford Mustang (2 door)
3. 1968 Volkswagen "Beetle" (2 door)
4. 1971 Ford Pinto (2 door)
5. 1966 Oldsmobile "88" (4 door sedan)
6. 1971 Chevrolet "Vega" (2 door)

Each of the above vehicles was modified so that an experimenter could select the escape route(s) available to the subjects which would allow them to exit the vehicle. The possible escape routes for each vehicle were those windows which could be opened and were of sufficient size to permit egress of the passengers, and the doors. Subjects were not permitted to break windows or use any exit other than doors or adjustable windows. The experimenter was also capable of controlling certain exterior environmental elements. For example, each vehicle was modified to produce an "explosion" under the hood with concomitant flames that could be seen in a sheet shooting across the front window. In addition, smoke from the explosion completely engulfed the immediate exterior of the automobile. These modifications could not be detected by the subjects.

(a) <u>Control of escape routes</u>--A four-door vehicle has eight escape routes (four doors and four windows). The two door vehicles have either four or six exits (two doors and either two front windows and two rear windows or two front windows only).

The escape routes were controlled by two methods dependent upon the vehicle. In the case of the vehicles equipped with electric windows (Toronado and Oldsmobile "88"), the windows were locked electrically by using electrical relays to open the power circuit to the window drive motor. These relays were operable from the experimenter's control panel located approximately 25 ft from the test vehicle.

Manually operated vehicle windows were jammed by a pneumatic air cylinder located inside the door or, in the case of two door vehicles, inside the side panel for the rear windows. The mounting of the cylinder was peculiar to each vehicle. The cylinder had a rod that protruded from the cylinder when air pressure was applied. The cylinder was mounted so that movement of the window, window level, or the gears was impeded. Operation of the window was not hampered when the cylinder was not activated.

The doors in all vehicles were jammed by larger pneumatic cylinders. The cylinders were mounted inside the door so that when activated, the rod would protrude through an opening in the bottom of the door and another opening in the frame of the vehicle, thus locking the door.

Concealed air tubes were connected to the air cylinders via the bottom of the vehicle. The end of each tube was connected to a manual valve at the control panel. These valves were jointly connected to a servo-valve which was also connected to a tank of compressed air. The air tank was maintained between 70 psi and 125 psi pressure.

Once the appropriate manual valves at the control panel were opened, the cylinders were activated in unison when the servo-valve was opened. The operator at the control panel could close all escape routes by opening all of the valves or any combination that he desired by opening some and closing others. Although the set-up for each experimental trial took as much as a minute, the actual locking of the doors and windows took only a small fraction of a second and was accomplished remotely after the subjects were placed in the vehicle prior to each trial.

For vehicles with electric windows, one switch activated both the relays and the servo-valve in unison.

(b) Environmental control--Efforts were made to simulate a post-crash panic situation. The engine was running at all times during the trials. The panic situation was not intended to simulate a post-crash fire but it was intended to induce panic in the subjects under controlled experimental conditions. The situation depicted in the experiment was an engine explosion and fire. The equipment used to produce the panic situation is described below.

The explosion was caused by a miniature cannon mounted near the motor under the hood of the vehicle. The cannon was approximately 8 in long and 3/4 in in diameter with a 3/8 in bore. The cannon was loaded by packing gun powder in the barrel and stuffing paper behind the powder in the hole. The powder was ignited by shorting the poles (utilizing a magnetic relay mounted on the experimenter's control panel) on the car battery and heating a nichrome wire which was inserted in the powder. The wire melted and ignited the powder causing a loud explosion.

The smoke was caused in a similar manner with the powder being spread in an open pan. When the powder was ignited by shorting the battery, a dense white smoke engulfed the front of the vehicle.

Flames appeared to cover the front windshield of the vehicle following the explosion. For a vehicle with hidden windshield wipers, the flame apparently came from under the hood, and for the other vehicles the flames appeared to originate from the air vent near the front windshield. A butane tank was located in the trunk of the vehicle being tested with a line connected to a servo-valve under the hood. A 24 in brass tube with holes hidden from the view of the subjects was connected to the servo-valve. A pilot light was on continuously so that when the servo-valve was activated the flames would shoot across the windshield. Again the servo-valve was activated at the control panel.

The explosion, smoke and flames occurred simultaneously. As soon as the explosion occurred, a nearby experimenter used a fire extinguisher in a planned futile attempt to extinguish the fire in order to add realism by simulating an engine fire.

(c) Signal devices--The subjects were signaled to begin their escape by an auditory signal mounted below the vehicle. The tone of approximately 600 cps was continued through the entirety of each trial.

A dim light hidden from the view of the subjects was the ready signal for the experimenters (usually eight persons). The light was usually turned on approximately ten seconds prior to the start of a trial.

Both the auditory and the visual signal were activated at the control panel.

(d) The control panel--Included on the control panel were:

1. Main power switch
2. 4 window air valves and servo-valve
3. 4 door air valves and servo-valve
4. 4 switches for electric window deactivation
5. 1 switch for explosion control
6. 1 switch for smoke control
7. 1 switch for fire control
8. 1 auditory signal activation switch
9. 1 visual signal activation switch
10. 1 timer activation switch

Switches were placed on the control panel so as to facilitate accurate and timely activation prior to and during an experimental trial.

(e) Timers--Two digital timers (placed on each side of the vehicle) designed to read to the nearest 0.01 minute were utilized to measure the time to escape for each subject during a trial.

3.1.2.3 Subjects: The subjects were selected according to age and sex. The nature of the experiment demanded that subjects be in reasonably good health.

Rather than take a cross-section of all ages, two distinct age groups were selected so that resultant suggestions might be applicable to younger or older persons.

The ages selected were designed to exclude the novice vehicle driver of ages sixteen, seventeen and eighteen. Drivers of these ages are frequently under direct parental supervision and often drive with their parents. In this light, the age of nineteen was arbitrarily selected as the minimum age for the younger age group. At an age of nineteen, a person might be expected to be either in college or working on his own and hence have some degree of independence and autonomy with respect to his driving habits.

The upper limit for the younger age group was set at twenty-nine. Those persons from age nineteen to twenty-nine will be referred to as the younger group.

The boundary limits were extended for determination of the older age group. The lower limit of the older age group was set at thirty-nine while the upper limit was set at fifty-nine. A practical consideration here was the availability of subjects in the older age group. If the age range had been restricted to a ten year span, it would have been extremely difficult to find enough subjects. The age group from thirty-nine to fifty-nine will be referred to as the older age group.

The other consideration was general health and physical condition of the subject. Each subject, although not given a physical examination, was asked prior to the experiment about his medical history. Any present or past medical problem which might be aggravated by extreme mental or physical stress excluded the subject from participation. Heart conditions and high blood pressure are examples of unacceptable conditions. Also, each subject was asked for weight, height, and age. These figures were checked against the Air Force requirement chart for weight, height and age. Only persons above the 10th and below the 90th percentile in weight for their sex and age group were permitted to participate. The rationale behind restrictions on weight, height and age was again safety. An obese or unusually frail individual would be more susceptible to injury than normally sized persons. Also, if inordinately large or small persons were allowed to participate, it is conceivable that a ninety pound female might be confronted with lifting a two hundred pound male who was participating as an injured passenger to be rescued. Therefore, persons in good health with weight commensurate with height and age were used as subjects.

A description of the anthropometric data taken for each subject is given in the following paragraphs.

(a) Anthropometric data--The following anthropometric data was taken for all subjects.

1. Age
2. Height
3. Weight
4. Shoulder Breadth
5. Elbow Breadth
6. Seat Breadth

Height and weight were stated by the subject. Shoulder breadth and seat breadth were taken with the subject seated on a flat wooden surface with the arms about 90 degrees at the elbow and pressed tightly against the sides. Seat breadth was taken in the same position with the knees together.

Two additional measurements were added later in the experimental series in order to achieve a better description of each subject's overall body shape. These measurements are:

1. Extended Shoulder Breadth
2. Trunk Depth

Extended shoulder breadth was taken with the subject standing and the arms outstretched upward over the head with the hands clasped. The widest point at the shoulders was recorded. Trunk depth was measured at buttock height with the subject standing, and the maximum dimension at this point was recorded.

All measurements were taken with sliding calipers to the nearest 1/8 in and are included in summary form in Table 3.1 below.

3.1.2.4 Experimental design: The experimental design included five main factors which are the independent variables. Figure 3.1 shows the breakdown for each vehicle. The independent variables are:

1. Type of Vehicle (5 levels)
2. Age Group (2 levels)
3. Sex Group (3 levels)
4. Escape Route (5 levels)
5. Occupant Condition (4 levels)

There were two dependent variables:

1. Time for the first person to escape
2. Time for all persons to escape from the vehicle

(a) Independent variables--

(1) Vehicles--Five vehicles were used initially to investigate escape worthiness. They were chosen to represent an adequate cross-section of passenger vehicles on American roads. They were:

1. 1969 Toronado (2 door hardtop)
2. 1967 Ford Mustang (2 door)
3. 1968 Volkswagen (2 door)
4. 1971 Pinto (2 door)
5. 1968 Oldsmobile "88" (4 door sedan)

TABLE 3.1

ANTHROPOMETRIC DESCRIPTION SUMMARY FOR SUBJECTS

		Older Females	Older Males	Younger Females	Younger Males
Age (yrs)	Max.	57	63	27	29
	Min.	39	39	19	18
	Median	46	47	21	22
Height (ft,in)	Max.	5'8"	6'2"	5'9"	6'4"
	Min.	5'0"	5'3"	5'0"	5'8"
	Median	5'4"	5'10"	5'5"	5'11"
Weight (lbs)	Max.	150	210	176	215
	Min.	108	138	90	135
	Median	135	179	120	165
Shoulder Breadth (in)	Max.	16 1/2	19 3/4	16 1/2	20
	Min.	14 1/4	14 1/2	14 1/4	15
	Median	15 1/2	17 1/4	15 1/4	17 1/2
Elbow Breadth (in)	Max.	19 3/4	21 3/4	18 3/4	23
	Min.	14	14	13 1/2	15 1/2
	Median	16 1/4	18	15 1/4	17 1/2
Seat Breadth (in)	Max.	16 1/2	17 1/2	17 1/4	17 1/2
	Min.	13	13 1/4	12 1/4	12 3/4
	Median	15	15 1/4	14 1/2	14 1/2
Extended Shoulder Breadth (in)	Max.	16 3/4	20 3/4	15 3/4	15 3/4
	Min.	12	13	11	13 1/2
	Median	15	14 3/4	13 1/4	14 1/2
Trunk Depth (in)	Max.	10 3/4	11 1/4	8 3/4	9 1/4
	Min.	5 3/4	8	5 3/4	7 1/4
	Median	7 1/4	9 1/2	7 1/4	7 3/4

Age Grouping		Younger (19-29)														
Sex Grouping		Male					Female					Mixed				
Escape Routes		1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
	NI	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Occupant* Condition	I	X		X	X	X	X	X	X	X	X	X	X	X	X	
	IC		X													X
	P			X						X			X			

Age Grouping		Older (39-59)														
Sex Grouping		Male					Female					Mixed				
Escape Routes		1	2	3	4	5	1	2	3	4	5	1	2	3	4	5
	NI	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Occupant* Condition	I	X	X	X	X		X		X	X	X	X	X	X	X	X
	IC					X		X								
	P		X						X						X	

Escape Routes
1. Two doors
2. One door (driver's side)
3. All windows
4. Two windows (driver's side)
5. One window (driver's side)

Occupant Condition	
NI	No Injuries
I	One injury
IC	One injury, where injured person is in path of only available exit
P	Experimentally induced panic with no injuries

*Applicable conditions are denoted by an X

Figure 3.1. Experimental Design-Emergency Vehicle Egress (Replicated for Each Vehicle).

(2) Age groups--The age groups were discussed in detail in Section 3.1.2.3. These were:

1. Younger Group (ages 19-29)
2. Older Group (ages 39-59)

(3) Sex groups--Each of these age groups was broken down into three sex groupings. They were:

1. Four males
2. Four females
3. Mixed (2 males and 2 females)

An age and sex classification comprised the testing group. For example, one group of all males between nineteen and twenty-nine years old was tested to completion for one vehicle. Therefore, each vehicle was tested with six age-sex groups (2 age groups x 3 sex groups) of four subjects each.

(4) Escape routes--The next independent variable was the escape route which the subjects were allowed to take for each trial. They were:

1. 2 doors
2. 1 door (driver's side)
3. All windows
4. Two windows
5. One window

These escape routes were chosen to represent a wide range of escape routes. Upon impact any one or combination of possible escape routes may be available to the driver and passengers of an automobile. In post-crash conditions a door or window may be jammed or a fire may block an exit attempt.

Five of a large number of possible combinations were selected for investigation based on decreasing number and area of the possible escape routes available.

For the two door situation, the driver's door and the door adjacent him were available for exit. As in each combination of escape routes, all other possible exits (windows and doors) were locked.

For the one door situation, all exits were locked except the driver's door.

The all window condition allowed all moveable windows to be used as exits. All doors were locked.

Two windows were available to the subjects for escape in the two window situation. They were the driver's window and the window in the rear on the driver's side. For some vehicles, the all windows and the two windows conditions were the same. In these vehicles the rear seat window was not moveable (Pinto, Volkswagen).

All exits but the driver's window were locked for the one window situation.

(5) Occupant conditions--The occupant's condition had four levels. They were:

1. No injuries
2. One injury
3. One injury with conflict
4. Panic

The no injury condition is self-explanatory. No subjects were to be considered injured.

In the one injury condition, one of the subjects was designated as being injured. This subject was instructed to act as though he was unconscious at the start of a particular escape trial. He was also instructed to conceal his identity until the start of the trial.

The one injury with conflict was a special case of the one injury condition. The conflict arose when the injured person was blocking the only available exit (i.e., injured driver when only exit is the driver's window).

The panic situation was a special case of the no injury condition. Panic was induced experimentally by an explosion followed by smoke and flames.

The experiment was replicated so that each one of the five escape routes would have no injury and a one injury condition. The panic situation was a replication of a no injury condition. The five escape routes were tested twice (one injury and no injury) and the panic situation occurred once totaling eleven exit attempts or trials for each group. Both the younger and older groups had three sex groupings each totaling six groups. Therefore, there were a total of sixty-six escape trials for each vehicle (3 sex groups x 2 age groups x 11 exit attempts).

(b) <u>Dependent variables</u>--

(1) <u>First person escape time</u>--The first dependent variable was the time required for the

first person to escape. The timer was started at the signal to begin and was read when one person was completely free of the vehicle. The term "completely free" refers to a person being removed from the vehicle (not touching it) and being free from any entanglement with it (clothing, lap belt, etc.).

(2) Total escape time--The second dependent variable was the time that elapsed between the start of a trial and the escape of all persons in the vehicle. The measurement technique was similar to the first person escape time above except that all occupants had cleared the automobile at which time the timer was stopped.

(3) Controls--The environmental conditions were kept as static as possible for all experiments. The experiment was conducted in an enclosure with heating control only. All of the initial vehicles were tested during the winter and spring when the temperature could be held between 72°F and 80°F. Also, the test vehicle was highly illuminated for photographic purposes so that lighting was nearly the same for all trials.

Each vehicle was tested during an eight-hour period in one day so that all subject groups could be tested on the same day. Order of presentation of the escape routes was counterbalanced between age-sex groups within vehicles, although each vehicle had an identical escape route sequence for a given age-sex group.

Each group of subjects was given the same set of instructions and given adequate opportunities to familiarize themselves with the vehicle. The experiment did not begin until all subjects understood the instructions thoroughly and felt that they were familiar with the operation of apparatus used in escape from the vehicle (i.e., seat belts, door handles, door locks, etc.).

Debriefing sessions with each group of subjects were tape recorded following the completion of their experimental escape trials. The tapes were then used to provide qualitative insights into the escape worthiness problem. Information from the debriefing tapes is presented in condensed form in Section 3.1.3.3, Results.

3.1.2.5 Experimental procedure--daylight escape studies:

(a) Procedure--As subjects arrived at the testing center they were escorted to a special subject room. A registered nurse took anthropometric measurements for each subject immediately. Once all four of the subjects in a group had arrived, the project coordinator gave a preliminary briefing to explain the nature of the experiment. The following is a synopsis of that briefing:

> This study is conducted under the supervision of the Department of Industrial Engineering through the Oklahoma University

> Research Institute under a federal contract with the Department of Transportation. The purpose of the experiment is to investigate the escape worthiness of vehicles by changing the condition of subjects and the possible escape routes. Your job is to exit the vehicles as quickly as possible on a given signal.

After the short preliminary briefing, the subjects were escorted to the vehicle. The subjects lined up and were photographed holding their respective numbers so that they could be later identified by physical appearance. The coordinator then randomly seated each subject in the vehicle.

At this time the subjects were given an opportunity to familiarize themselves with the operation of the door handle, window handle, door locks and lap belts. If there were any questions, the mechanism was explained in greater detail.

The console operator locked the doors and windows and sounded the signal to start in order to give the subjects an idea of what to expect. A pre-trial briefing then proceeded as follows:

> Each subject will receive a folded slip of paper (subjects were shown an example) which will read either "injured" or "not injured" before each trial. For any one trial there may be any combination of injured and not injured slips passed out. Once you have noted which slip you have received please lay it aside. In either case do not let other members of the group know the type of slip you have received. If you receive a "not injured" slip, respond naturally to the signal to escape. If you received an "injured" slip, remain completely dormant. Exhibit no movement at all. In short, simulate unconsciousness at the signal to escape.

> You are to escape as quickly as possible using the available exit that will afford the most expedient escape, be it a window or a door. Those of you who are not injured will have to help the injured individual or individuals to escape. The signal to begin is the sound you heard earlier. Again I want to impress upon you the importance of expediency. Move as quickly as possible. Are there any questions?
>
> (Questions are then fielded.)

Following the pre-trial briefing the groups were then given a familiarization trial. After the escape, the group was led to the subject room. When they returned to the vehicle, they were asked if there were any questions. Once the group thoroughly understood the procedure, the trials began.

The sequence of possible escape routes remained the same for each group. However, combinations of injured and not injured subjects were varied (three sets for the six groups). The panic situation occurred at one of three escape routes (two groups per situation).

After each trial the group returned to the subject room and the vehicle was prepared for the next trial. The subjects returned to their same respective positions in the vehicle after each trial.

At the completion of testing the group was given a comprehensive debriefing that was recorded for more thorough analysis. The theme of the debriefing was vehicle escape worthiness. It was conducted in the form of a discussion giving the subjects an opportunity to interject any point that they thought pertinent to the theme, whether it was prompted by the experiment or not. Each group was asked certain questions.

1. Were there any design features of the testing vehicle that aided or deterred your ability to escape?
2. If so, how do you suggest they be improved or changed?
3. What were the effects of the panic situation on your ability to escape during the panic situation?
4. In general what suggestions do you have that may aid in making vehicle egress more expedient?

Following the debriefing, subjects were allowed to leave and another group of four arrived for testing.

(b) Personnel--The staffing required to conduct an experiment included a skeleton crew of five and a full crew of eight if the experiment was filmed. The staff positions were as follows:

1. Project coordinator-directed all activities during the course of the experiment.
2. Panel operator-mechanically set escape routes for each trial and controlled the "panic" trial.
3. Timer No. 1-measured escape time for the subjects on the opposite side from the driver (both front and back seat) also observed escape methods employed by the subjects, (i.e., number feet first vs. head first).
4. Timer No. 2-performed the same functions as Timer No. 1 for subjects on driver's side.

5. Registered Nurse-took anthropometric measurements, served as medical attendant in case of injury, and attended subjects during testing.
6. Cameraman No. 1-filmed action on the side opposite the driver.
7. Cameraman No. 2-filmed action on the driver's side.
8. Cameraman No. 3-took still pictures.

Each individual on the crew also performed additional functions which were guided by the situation. These jobs included operation of the fire extinguisher in an apparent attempt to extinguish the fire used on some trials, interviewing subjects during the debriefing, etc.

3.1.2.6 Night studies--vehicle escape worthiness--a pilot study:

(a) Introduction--The night studies were intended to investigate vehicle escape worthiness under post-crash darkness conditions. The studies were conducted in a similar manner to the day studies with a few minor modifications. The main deviation was the simulated starlight condition.

The experiment was run at night in the same enclosure used for the day time studies with the usual building illumination turned off. Soft, colored (red) lights were placed throughout the building to simulate the vehicle interior lighting intensity which would exist outdoors on a starlit night.

A pilot study was conducted to determine the feasibility of continuing the investigation of the night studies in a similar manner used for the day studies. In the pilot study only the younger age groups were used for subjects. It was agreed by the experimenters that the risk of injury to older, less agile subjects would be too great under these experimental conditions for them to be used.

As subjects arrived, they were given red goggles to wear for approximately thirty minutes in order to allow their eyes to adapt to the darkness. During this period prebriefings were conducted as usual.

The night experiments had two unresolvable problems. First, it was found that the subjects could not see well enough to escape the vehicle in a safe manner. Each person was functioning as an individual. Since there was no cooperation and coordination between subjects, the condition for escape could be described as hazardous. Subjects were unknowingly kicking, hitting and poking each other during their escape. Severe injury was likely to occur under these conditions. As subjects jumped from the vehicle, oftentimes they would land on one another. A broken limb may result from such conditions. The second problem was that experimenters had some difficulty in monitoring the activities of the subjects during the trials. Timers were required to recognize subjects by their physical appearance in order to evaluate accurately their time and escape endeavors. Even so, it was estimated that escape times were recorded with an accuracy comparable to the daylight escape trials.

Data was taken which could be compared to a comparable day study. However, further investigation was considered to be dangerous and impractical.

(b) Experimental design and procedure--night pilot study--A 1971 Chevrolet Vega was used as the test vehicle in the night study, which was designed to compare escape times under night conditions with day time escape results in the same vehicle; using the same general methodology.

Only "younger group" subjects and no "panic" conditions were used in this study for safety reasons. Therefore a total of 20 escape trials (2 sex groups x 10 trials) were accomplished under night conditions.

3.1.3 Results

3.1.3.1 Introduction: This section will present the results and discussion of the experiments outlined in the Methodology section (3.1.2) of this portion of the report. The results will be presented in three sections in the following order: Effects of Induced Panic and Fear on Escape Time, Passenger Car Results, and the Effects of Darkness on Escape Time.

3.1.3.2 Effects of induced panic and fear on escape time: The "panic" condition which was induced by an explosion and subsequent smoke and flames emanating from the vehicle was quite effective in achieving its purpose. The majority of the subjects that took part in the experiment, when interviewed after their portion of the experiment was completed, said that they thought some sort of "accident" had occurred that caused the vehicle to catch on fire. Even so, no significant difference could be found between either total or first person escape times in the panic condition and comparable no panic escape times.

Since this portion of the experiment may be considered as a four factor full factorial design (5 cars, 2 age groups, 3 escape routes (confounded with sex group), 2 passenger conditions (panic and non-panic)), the Analysis of Variance (ANOVA) model (BMD02V--computer analysis program--UCLA, 1969) was considered appropriate for statistical analysis. The ANOVA was considered to be a fixed effects model. The results of the ANOVA for the case where total time is the dependent variable are given in Table 3.2 below. Note that all of the main factors with the exception of passenger condition significantly affected total escape time. The mean total time to escape in the panic situation was 0.308 minutes while the corresponding non-panic trial mean was 0.306 minutes. Not only was escape time unaffected by the panic condition, the first order and second order interactions of the other variables with passenger condition were also not significant. Mean time for the first person to escape from the vehicle was 0.138 minutes for the panic condition while the non-panic comparable trials produced a mean first person escape time of 0.143 minutes.

The ANOVA for first person escape times showed essentially the same result as the ANOVA for total escape times and will not therefore be presented here.

One can only conclude that in the experiment conducted and reported herein, the induction of panic or fear did not either increase or decrease the total time or first person time to escape from an automobile when

TABLE 3.2

ANOVA TABLE FOR PANIC VS NON-PANIC CONDITION USING TOTAL ESCAPE TIME AS THE DEPENDENT VARIABLE

Source of Variation (Variable)	Degrees of Freedom	Sums of Squares	Mean Squares	F
1 (Vehicle)	4	0.46453	0.11613	13.3**
2 (Age Group)	1	0.29120	0.29120	33.4**
3 (Escape Route)	2	0.56484	0.28242	32.4**
4 (Passenger Condition)	1	0.00011	0.00011	<1
12	4	0.12796	0.03199	3.66
13	8	0.26200	0.03275	3.75*
14	4	0.00533	0.00133	<1
23	2	0.18789	0.09395	10.75**
24	1	0.01803	0.01803	2.07
34	2	0.04177	0.02089	2.39
123	8	0.11724	0.01465	
124	4	0.00411	0.00103	
134	8	0.04149	0.00519	
234	2	0.03601	0.01801	
RESIDUAL	8	0.06994	0.00874	
TOTAL	59	2.23245		

*Significant at $\alpha = .05$.

**Significant at $\alpha = .01$.

compared to similar "non-panic" trials. The transferability of this result to the case of an accident involving psychological and physiological trauma is a difficult question to address. However, one might propose that escape times in real accident situations where the occupants of the vehicle are familiar with the operation of the seat belts, door handles, etc., would probably not be affected adversely by a panic situation threatening to life in most cases.

3.1.3.3 Passenger car results:

(a) Introduction--This section represents the major portion of the effort involving data collection for the passenger car escape on land portion of this study. The experimental design for this section is a five factor (5 cars, 5 escape routes, 2 age groups, 2 passenger conditions--injured and not injured, 3 sex groups) full factorial design. Note that "panic" trials are not considered in this data, since it was considered in the previous section.

(b) Quantitative results--The appropriate statistical technique for the analysis of this data is the fixed factor Analysis of Variance (ANOVA). Tables 3.3 and 3.4 contain the ANOVA summaries for the first person escape time and total escape time data. It is apparent from these summaries that both time for the first person to escape and total passenger escape time are significantly affected by all of the independent variables under consideration here. This result is partially intuitive. For example, one might expect that younger people, being more agile and having less fear of injury in this

TABLE 3.3

ANOVA SUMMARY TABLE--PASSENGER CAR RESULTS FIRST PERSON ESCAPE TIMES

Source of Variation (Variable)	Degrees of Freedom	Sums of Squares	Mean Squares	F
1 (Vehicle)	4	0.56010	0.14002	31.12**
2 (Escape Route)	4	0.96478	0.24119	53.48**
3 (Injury Situation)	1	0.39457	0.39457	87.49**
4 (Age Group)	1	0.37311	0.37311	82.73**
5 (Sex Group)	2	0.18875	0.09437	20.92**
12	16	0.15629	0.00977	2.09
13	4	0.01119	0.00280	< 1
14	4	0.17030	0.04258	9.43**
15	8	0.19953	0.02494	5.53**
23	4	0.15536	0.03884	8.61**
24	4	0.03403	0.00851	1.89
25	8	0.08949	0.01119	2.48*
34	1	0.00897	0.00897	1.99
35	2	0.00219	0.00109	<1
45	2	0.04193	0.02097	4.65*
123	16	0.05938	0.00371	
124	16	0.10462	0.00654	
125	32	0.26026	0.00813	
134	4	0.02479	0.00620	
135	8	0.01943	0.00243	
145	8	0.13407	0.01676	
234	4	0.00222	0.00055	
235	8	0.07506	0.00938	
245	8	0.18434	0.02304	
345	2	0.01468	0.00734	
1234	16	0.07575	0.00473	
1235	32	0.14007	0.00438	
1245	32	0.24033	0.00751	
1345	8	0.05376	0.00672	
2345	8	0.26917	0.03365	
RESIDUAL	32	0.14429	0.00451	
TOTAL	299	5.15282		

* Significant at $\alpha = .05$
** Significant at $\alpha = .01$

TABLE 3.4

ANOVA SUMMARY TABLE--PASSENGER CAR RESULTS--TOTAL ESCAPE TIME

Source of Variation (Variable)	Degrees of Freedom	Sums of Squares	Mean Squares	F
1 (Vehicle)	4	2.93751	0.73438	39.4**
2 (Escape Route)	4	4.51439	1.12860	60.5**
3 (Injury Situation)	1	5.27198	5.27198	283 **
4 (Age Group)	1	1.98940	1.98940	106.5**
5 (Sex Group)	2	1.58066	0.79033	42.3**
12	16	0.94095	0.05881	3.15**
13	4	0.19366	0.04842	2.59
14	4	0.47218	0.11804	6.34**
15	8	1.01350	0.12669	5.80**
23	4	1.02429	0.25607	13.72**
24	4	0.36380	0.09095	4.87*
25	8	0.55951	0.06994	3.74**
34	1	0.09918	0.09918	5.31*
35	2	0.16053	0.08027	4.30*
45	2	0.54081	0.27041	14.55**
123	15	0.30167	0.01885	
124	16	0.36375	0.02273	
125	32	0.75584	0.02362	
134	4	0.06465	0.01616	
135	8	0.07350	0.00919	
145	8	0.74424	0.09303	
234	4	0.13537	0.03384	
235	8	0.21614	0.02702	
245	8	0.54162	0.06770	
345	2	0.02148	0.01074	
1234	16	0.25705	0.01607	
1235	32	0.42143	0.01317	
1245	32	0.95745	0.02992	
1345	8	0.07591	0.00949	
2345	8	0.46881	0.05860	
RESIDUAL	32	0.59697	0.01866	
TOTAL	299	27.65799		

* Significant at $\alpha = .05$
** Significant at $\alpha = .01$

experiment, would require less time to escape than older persons. Also, it is reasonable to expect that an injury to one of the passengers causing him to lose consciousness would cause a significant increase in escape time over the situation where no one was injured. Some of the results, however, were not subject to intuitive prediction. This can be seen from Figures 3.2 to 3.6 which present the mean first person and total escape times for each of the levels of the five independent variables considered in this experiment. Each figure will be discussed in the following paragraphs. The discrete points are connected for visual effect.

Figure 3.2: A Duncan Multiple Range test on the marginal means represented in this figure indicate the following: First person escape time from the Volkswagen was significantly longer than that of the other four vehicles. Total escape time from the Volkswagen was significantly greater than the Toronado, Mustang or Oldsmobile while total escape time from the Pinto was significantly less than those three vehicles. This result is surprising since the Pinto and the Volkswagen may both be considered as compact cars. The vehicles differ, however, in their internal allocation of space, especially within the passenger compartment. It is apparently not the external size of an automobile that indicates its escape worthiness then, but perhaps other factors such as the design parameters of the vehicle interior which are related to short escape times. The Volkswagen appeared to provide

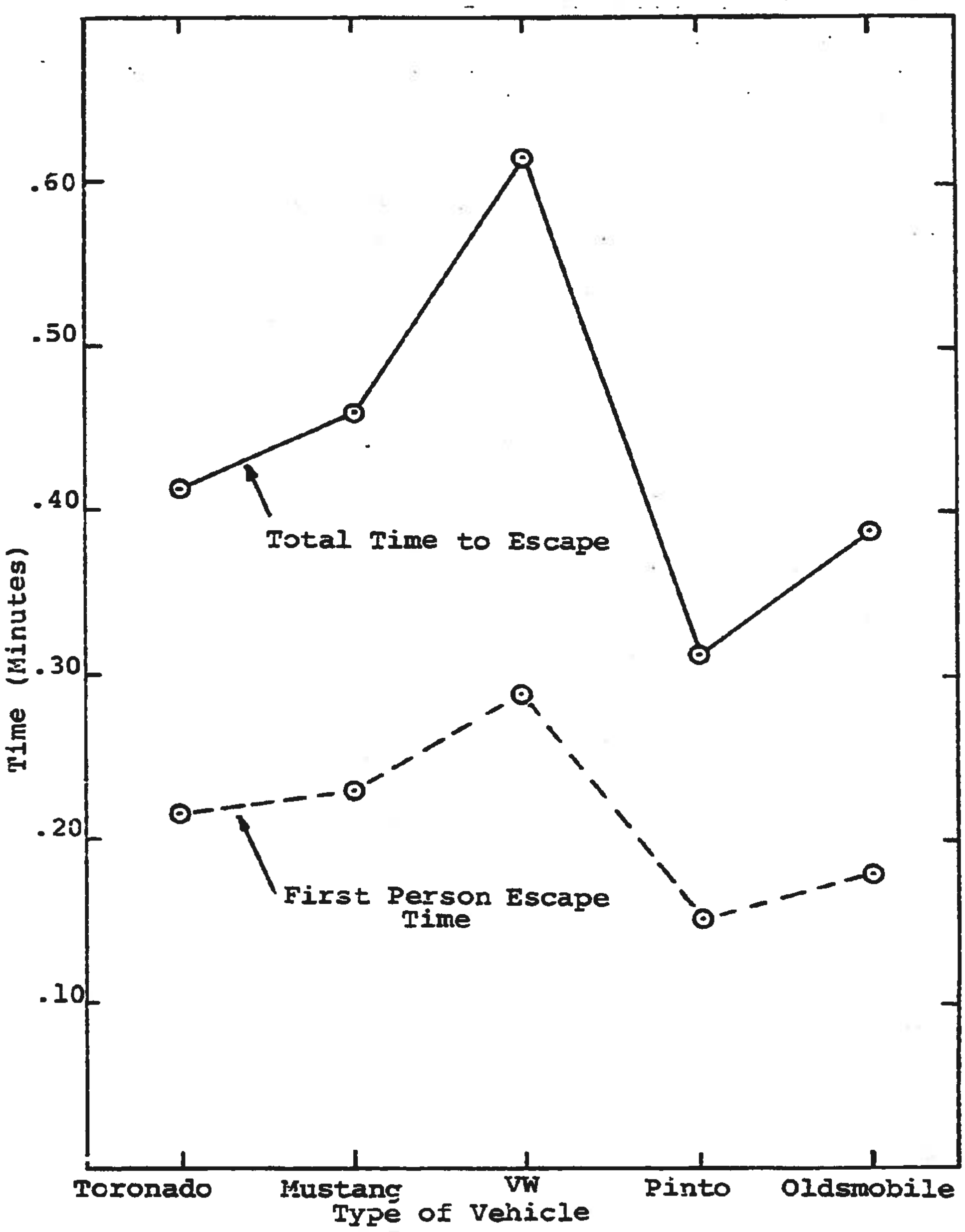


Figure 3.2. Graphical depiction of first person and total escape times as a function of vehicle type.

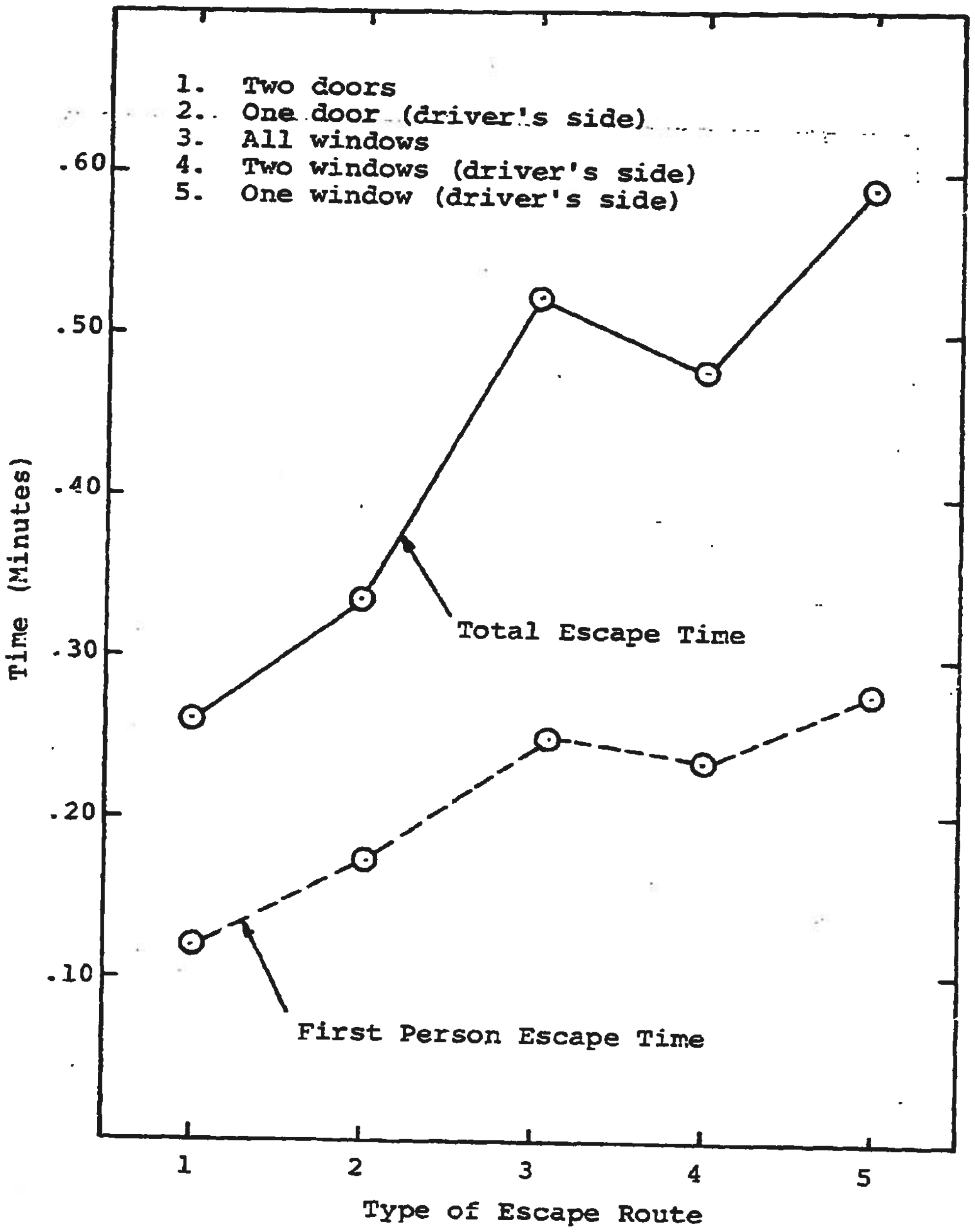


Figure 3.3. Graphical depiction of first person and total escape times as a function of available escape route.

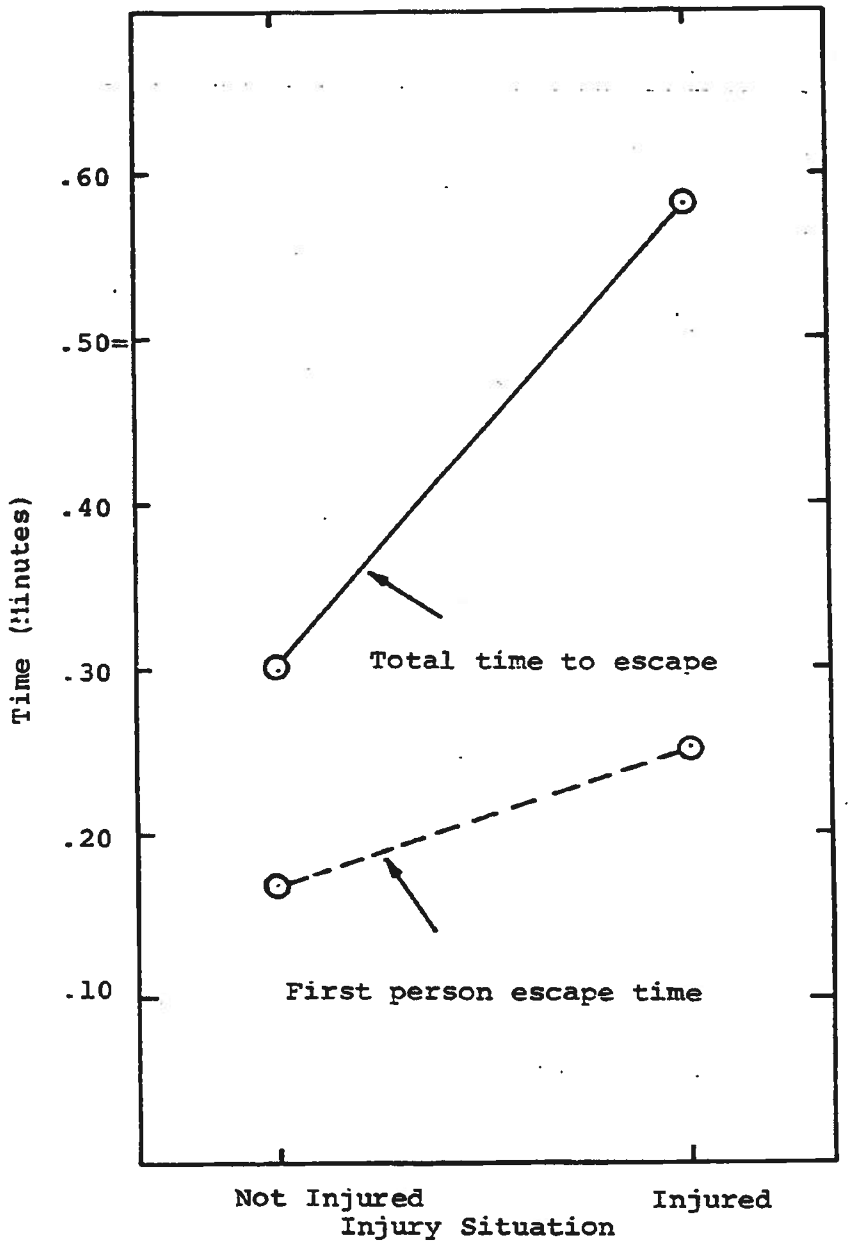


Figure 3.4. Graphical depiction of first person and total escape times as a function of passenger injury situation.

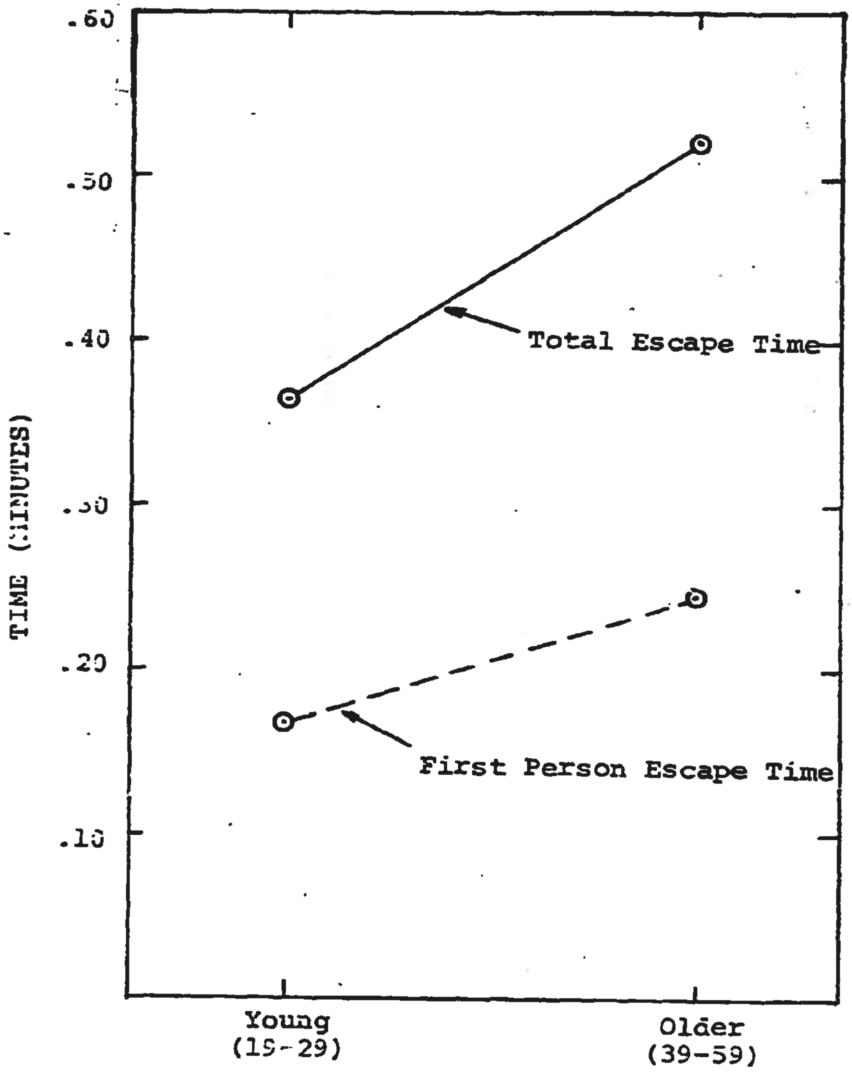


Figure 3.5. Graphical depiction of first person and total escape times as a function of subject age group.

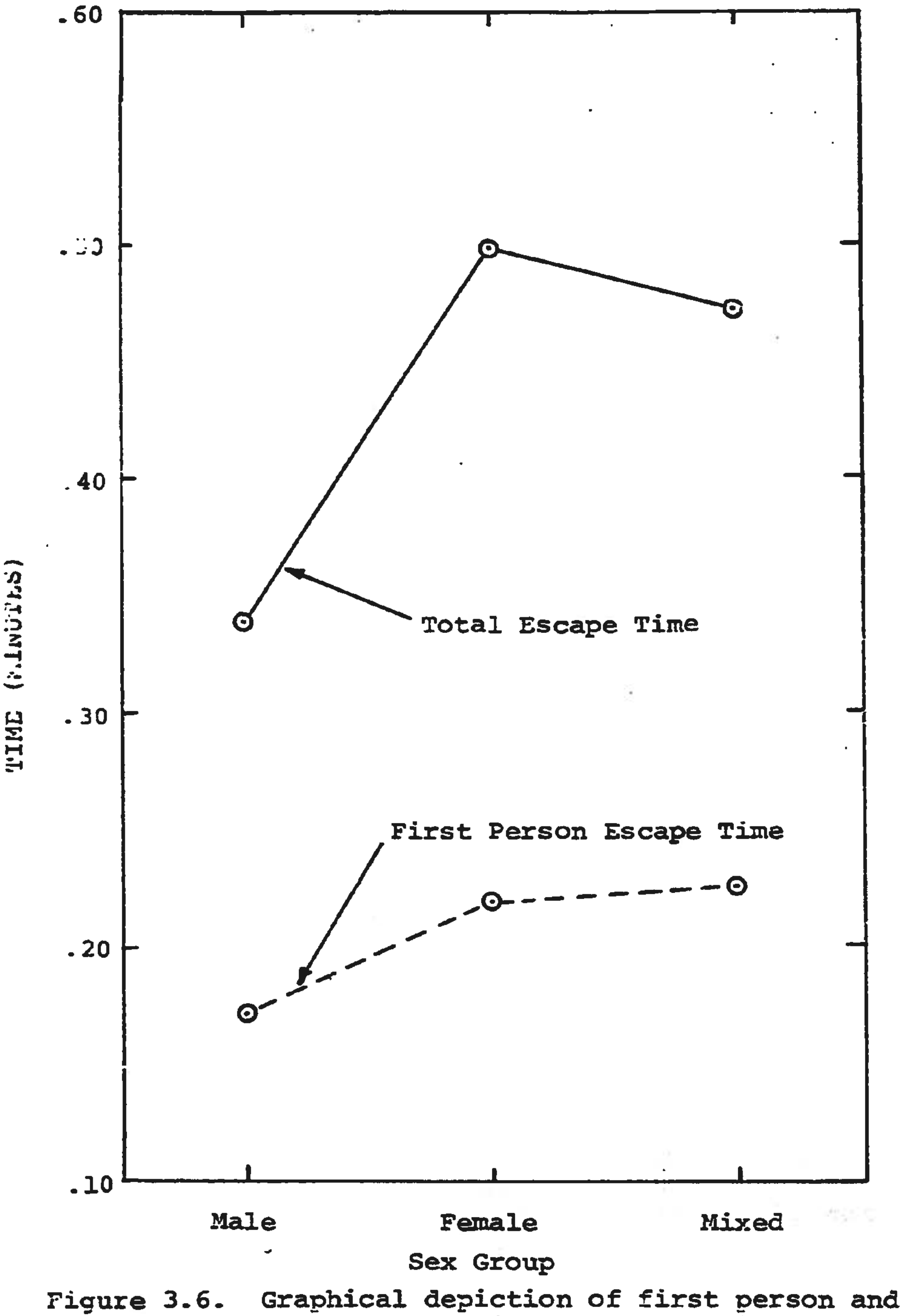


Figure 3.6. Graphical depiction of first person and total escape times as a function of subject sex group.

a great deal of difficulty, especially to Older Females when one of the passengers was designated as injured. In one particular case, where two windows (driver's and right front passenger's) were available for escape and the driver simulated injury, the older female group could not extricate the injured passenger and after two minutes the trial was terminated by the experimenter.

Figure 3.3: The escape routes involving one or two doors took significantly less time for both first person and total escape from a vehicle than the condition where the doors were jammed and only windows were available for escape. The case of all doors in the automobile being jammed appeared from this study to increase escape times by 60 to 80 percent. Note that this number is derived from a study where the subjects were familiar with their vehicle and had a psychological set to escape as quickly as possible. The increase noted above, then, must be considered as the minimum escape time increase one might expect when doors become jammed and windows become the only avenue of escape.

Figure 3.4: The total time to escape portion of this figure is the relevant data of interest here, since at least one or even two persons are in the vehicle with the subject feigning injury until he is removed. Note that one injured person increases the total escape time by more than 90 percent. The result is qualitatively intuitive. Again, caution must be exercised here in the

interpretation of this data. One must consider the increase above as the minimum to be expected under actual conditions, with the probability that the increase in escape time due to passenger injury under actual conditions would be much greater due to shock, disorientation and decision times regarding removal of the injured, etc.

Figure 3.5: Another "intuitive" result is presented in this figure. The older group took significantly more time to escape than the younger group in both the first person and total escape time cases. Agility and lack of fear of injury on the part of the younger group is probably responsible for the bulk of this result.

Figure 3.6: The results depicted in this figure probably occurred because of two factors: inherently greater strength in the male (for handling the "injured") and social predispositions of the behavior of the females escaping alone and in mixed groups. Note that the mixed-sex and all female subject groups tended to require a significantly greater time to escape than the all male groups. The social amenities of the situation undoubtedly slowed both the mixed and female groups somewhat. In an emergency situation, these social constraints would possibly have less influence on the escape situation than in this experiment.

Some of the more interesting first order interactions are depicted graphically in Figures 3.7 through 3.9.

Figure 3.7 represents the Vehicle vs Escape Route interaction for total escape time. Note that the Volkswagen has consistently longer mean escape times than the other vehicles for all escape routes. The difference becomes especially pronounced when the doors are unavailable for exit use. On the other hand, total escape time for the Pinto was consistently lower than the other vehicles regardless of the escape route available.

Figure 3.8 (Vehicle vs Injury Situation Interaction) shows that mean escape for the injured passenger case differs from the non-injured situation to a greater degree in the Volkswagen than in the other vehicles tested. In other words, an "injury" to a passenger in the Volkswagen in this experiment caused a greater increase in average total escape time than in any other vehicle tested. Even though this result is slightly less than the level for statistical significance at the $\alpha = 0.05$ level, it is worthy of mention.

Figure 3.9 (Vehicle vs Age Group Interaction) indicates that the total-time-to-escape differential between younger and older groups is accentuated to a much greater degree in the Volkswagen when compared to any of the other vehicles tested. Note that this phenomenon is not present in the Pinto which also may be considered as a sub-compact automobile.

Some other observations of interest from the interactions include:

1. On the average, total time for females to escape from the Volkswagen was 150 percent

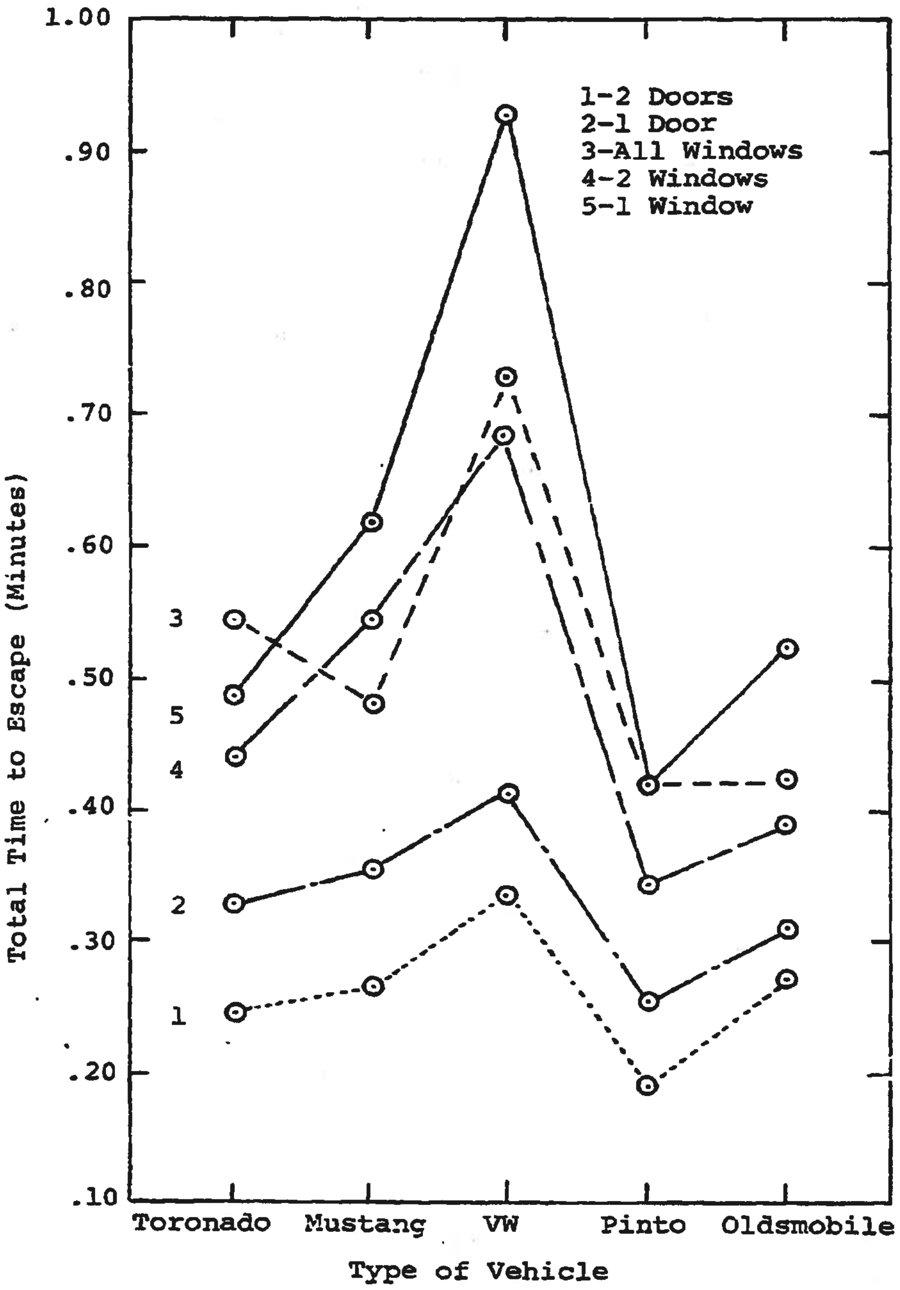


Figure 3.7. Graphical depiction of the first order interaction: total escape time as a function of vehicle type for different escape routes.

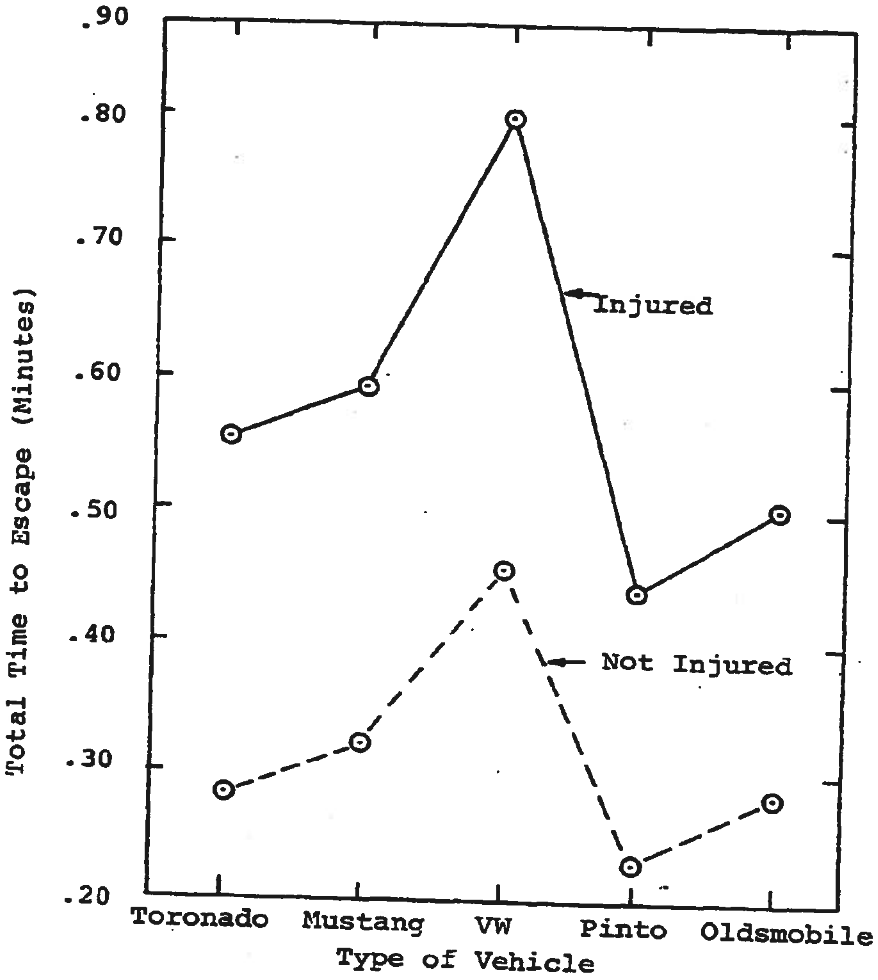


Figure 3.8. Graphical depiction of the first order interaction: total escape time as a function of vehicle type for different injury situations.

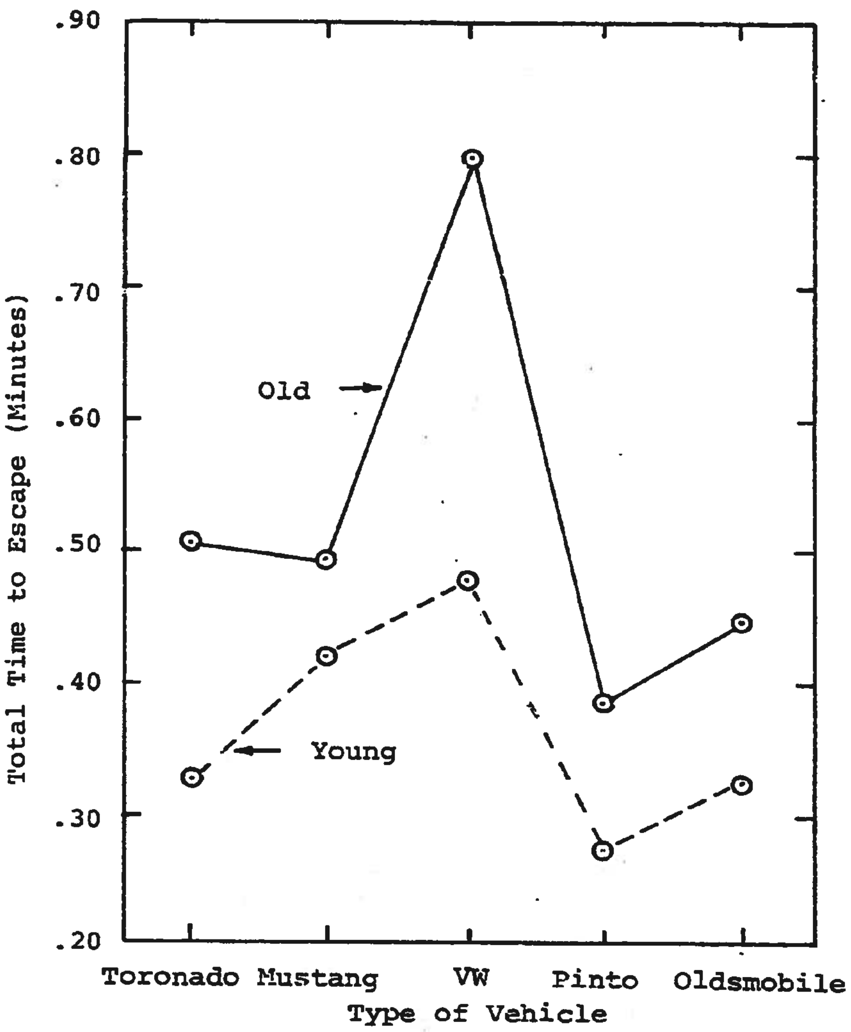


Figure 3.9. Graphical depiction of the first order interaction: total escape time as a function of vehicle type for different age groups.

greater than the time to escape from the Pinto.

2. The female and mixed sex group showed an inordinately large increase in escape time when doors were unavailable for escape compared to the case where they were available when these groups are compared to the male subject groups.
3. Total escape times for the older subject groups were increased (when injury was present) a great deal more than for the younger subject groups when one of their group was injured.
4. Female and mixed sex groups' total escape time increased (when injury was present) a great deal more than did the all male subject groups' when one of their group was injured.

Marginal mean data used in plotting the main effects as well as the first order interactions are given in Tables 3.5 and 3.6. It is apparent from the data that interior vehicle design parameters are of greater importance than external dimensions to the problem of escape worthiness as it was addressed in this experiment.

(c) Qualitative results--In the debriefing session following the experimental trials for each group of subjects, the subjects were asked questions relating to any difficulties they may have had in attempting to escape from the vehicle. There was one general comment mentioned by at least one person in all of the 30 sex-age-subject groups used in this experiment.

TABLE 3.5

MARGINAL MEANS--MAIN FACTORS--DAY ESCAPE DATA (IN MINUTES)

Variables	Mean First Person Escape Time	Mean Total Escape Time
Type of Vehicle		
Toronado	0.21	0.41
Mustang	.23	.45
Volkswagen	.28	.62
Pinto	.15	.33
Oldsmobile	.18	.38
Escape Routes		
2 Doors	.11	.26
1 Door	.17	.33
All Windows	.24	.52
2 Windows	.24	.48
1 Window	.27	.60
Occupant Condition		
Not Injured	.17	.31
Injured	.24	.57
Age Group		
Younger	.17	.36
Older	.24	.52
Sex Group		
Male	.17	.34
Female	.22	.50
Mixed	.23	.48

TABLE 3.6

MARGINAL MEANS FOR TOTAL ESCAPE TIME DATA: DAY TRIALS

First Order Interactions with Type of Vehicle

	Type of Vehicle				
	Toronado	Mustang	Volks-wagen	Pinto	Olds-mobile
Escape Route					
2 Doors	0.25	0.27	0.34	0.19	0.28
1 Door	.33	.36	.42	.26	.31
All Windows	.55	.48	.73	.42	.43
2 Windows	.44	.55	.69	.35	.39
1 Window	.48	.62	.93	.42	.52
Occupant Condition					
Not Injured	.28	.31	.44	.23	.27
Injured	.54	.59	.80	.43	.50
Age Group					
Younger	.32	.41	.47	.27	.33
Older	.50	.50	.77	.39	.44
Sex Group					
Male	.37	.37	.39	.26	.30
Female	.43	.51	.83	.33	.42
Mixed	.43	.48	.65	.40	.43

First Order Interactions with Escape Route

	Escape Route				
	2 Doors	1 Door	All Windows	2 Windows	1 Window
Occupant Condition					
Not Injured	0.19	0.22	0.32	0.41	0.40
Injured	.33	.44	.72	.56	.80
Age Group					
Younger	.22	.28	.39	.41	.48
Older	.31	.39	.65	.55	.71
Sex Group					
Male	.20	.30	.36	.37	.45
Female	.29	.36	.57	.57	.73
Mixed	.30	.34	.63	.50	.61

First Order Interactions with Occupant Condition

	Occupant Condition	
	Not Injured	Injured
Age Group		
Younger	0.24	0.47
Older	.37	.67
Sex Group		
Male	.24	.44
Female	.36	.65
Mixed	.33	.63

The subjects invariably stated that the lack of standardization of operation and location of door opening mechanisms, window cranks, door locks, front seat-back latches and lap belt/ shoulder harness locking mechanisms noticeably hampered their escape. Certainly, the period of demonstration, familiarization and practice for each subject group <u>before</u> the experiment began tended to minimize these problems. The fact that the subjects still considered the problem of placement and operation to be of major importance is, therefore, an extremely significant qualitative result. If we consider that the incidence of persons riding as passengers in vehicles with which they are unfamiliar is quite common in our society, then the problem under discussion here may be an extremely important one. Many of the subjects commented that the experience of participating in this experiment was quite helpful to them. They said that they had not thought about the problem of escaping from a vehicle in an emergency situation before and found the experiment extremely interesting and informative. Some of the subjects said that they were going to have "escape drills" with their families.

Some specific comments by the subjects concerning the vehicles were the following:

1. "There was no manual way to open the power windows, in the event that the doors jammed and the windows became inoperable." (Toronado)
2. "It is difficult (for a passenger) to reach the door handle from the rear seat

when the person in front is unable to open the door." (Toronado and Volkswagen)

3. "Gear shift knob on the floor limits maneuverability within the front seat area." (Mustang and Volkswagen)
4. "Steering wheel interferes with removal of the driver if he is injured." (all vehicles)
5. "Having to lift the door lock button before the door would open is an obstacle to escape if you're not familiar with it." (all vehicles so equipped)

3.1.3.4 Results--night studies: Night studies involving a 1971 Chevrolet Vega were conducted for two subject groups: younger males and younger females. The results of the night studies and the comparative escape times (younger males and younger females only) for daytime studies are given in Table 3.7.

There was no significant difference in escape times as a result of a lack of illumination (simulated star-lit night) for either the male or female groups in the injured or non-injured condition. This was true for both first person and total escape times. This result was quite surprising to the experimenter in this study.

Undoubtedly, the effect of practice is related to the subject's ability to overcome the effects of visual degradation due to night conditions in this experiment. The subjects were also visually dark adapted.

Perhaps the fact that the subjects attempted to escape from the vehicle before the subjects who had escaped before them had cleared the egress area outside of the vehicle was also a factor. The situation resulted in a "pile-up" of subjects on the floor of the laboratory that did not occur in any of the day trials. The combined effects of shock, trauma, disorientation and darkness in

TABLE 3.7

TABLE OF MEAN TOTAL AND FIRST PERSON ESCAPE TIMES FOR THE 1971 CHEVROLET VEGA--NIGHT AND DAY TRIAL COMPARISONS

Subject-Group Description	Total Escape Time (Minutes)		First Person Escape Time (Minutes)	
	Night	Day	Night	Day
Young Male	0.29	0.32	0.14	0.14
Young Female	.41	.35	.14	.16
Mean for Male and Female Combined	.35	.34	.14	.15
Young Male Injured	.42	.43	.17	.19
Young Male Non-Injured	.15	.21	.10	.09
Young Female Injured	.59	.50	.14	.21
Young Female Non-Injured	.22	.21	.14	.11
Young Male and Female Combined (Injured)	.51	.47	.16	.20
Young Male and Female Combined (Non-Injured)	.19	.21	.12	.10

a real emergency situation were not tested here. Therefore, one must be careful not to conclude that darkness would have no effect on escape time in an actual emergency situation, based only on the results presented here.

In any event, as a result of this experiment it must be concluded that darkness had no noticeable effect on either total or first person escape times from the Vega in this experiment. Care must be taken not to generalize these results to the older subject groups, since they were not involved (for subject safety reasons) in the night studies.

3.1.4 Development of a Predictive Model

3.1.4.1 Introduction: In order to provide some degree of generality of the results obtained in this study, a multiple linear regression model was derived using data from the five vehicles tested in the "Daylight Escape Studies" portion of this experimental series.

The whole idea behind this effort was to determine whether various physical measurements or parameters of an automobile would be related to the time to escape from it in this experiment. Hopefully, then, the model could be used (if validation was successful) as a predictor of the relative degree of "escape worthiness" in any automobile whose physical parameters of interest fall within the range of those used to develop the model. The parameters and procedures for model development are given in the following paragraphs.

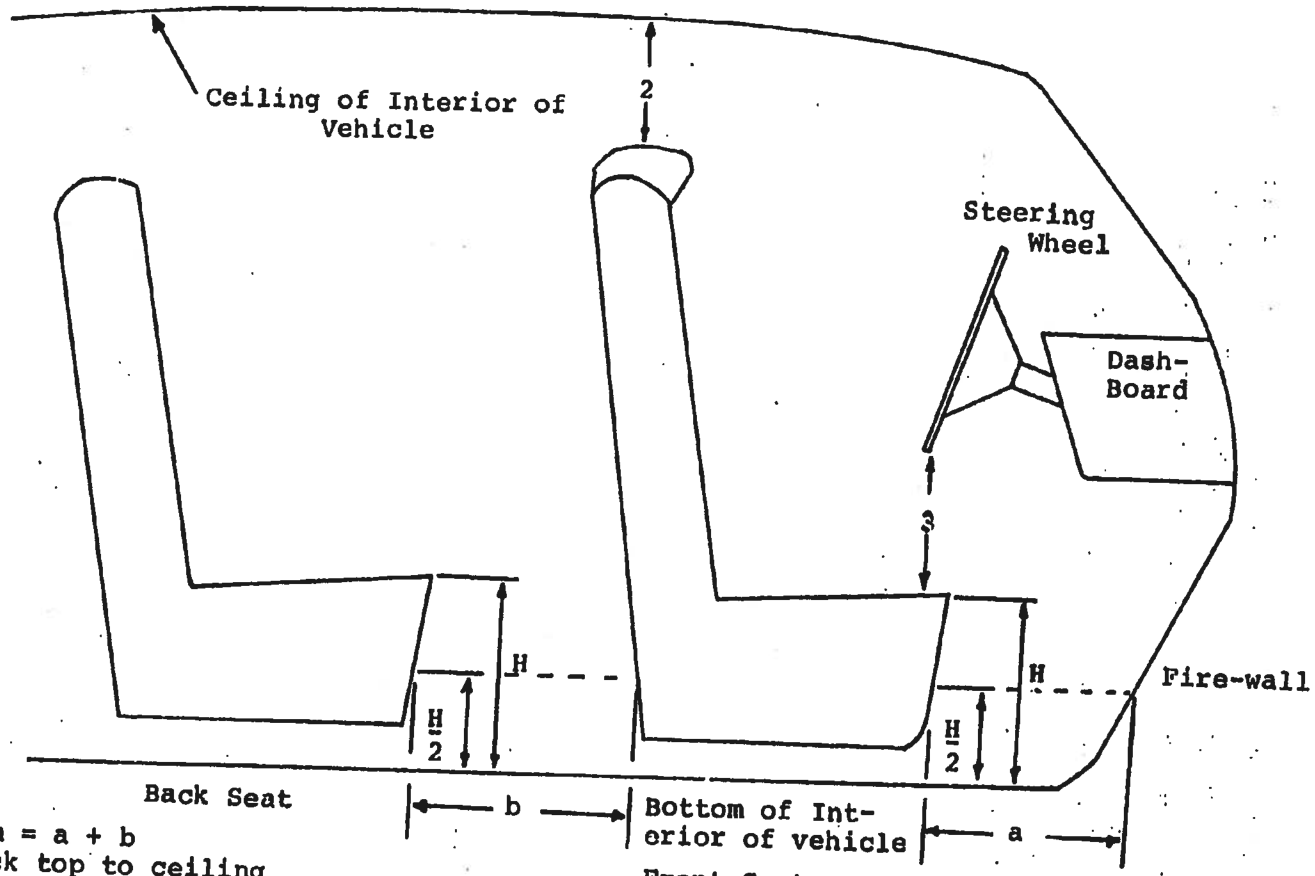
3.1.4.2 Parameters of the model: The parameters of the predictive model refer to the design characteristics and space allocation within the interior of a passenger car. Experimentation with the initial five automobiles, as detailed earlier in Section 3.1.3 provided insights as to which design characteristics are intuitively most important to facilitate a timely escape. In addition, an attempt was made to select the parameters so that at least a quasi-independence among the parameters in the model could be established.

The design parameters used in the model are the following:

1. <u>Leg room</u>--It consists of two parts:
    a. Distance between the leading edge of the front seat to the most forward point on the firewall where an individual could place his foot comfortably.
    b. Distance between the leading edge of the back seat to the rear edge of the front seat.

    Leg Room = (a) + (b)

    These distances were measured parallel to the ground (refer to Figure 3.10) and were measured at the plane which divides the height of the seat in two parts.
2. <u>Seat-back top to the ceiling</u>--Vertical distance between the top of the back of the front seat to the ceiling of the vehicle. The front seat was placed as far back as it will go and the head rest was extended to its maximum position (Figure 3.10).
3. <u>Seat top to steering wheel measurement</u>--Vertical distance between the uppermost point on the top of the front seat and the bottom of the steering wheel (Figure 3.10).
4. <u>Volume</u>--This measurement is an attempt to define a measure of <u>interior maneuverability</u>. The volume did not include the total internal volume but only the volume above a horizontal plane that was established by the bottom of the side-windows. The volume to the rear of the back seat was not included, but the volume over the dashboard was included.



1 Leg-room = a + b
2 Seat back top to ceiling
3 Seat top to steering wheel

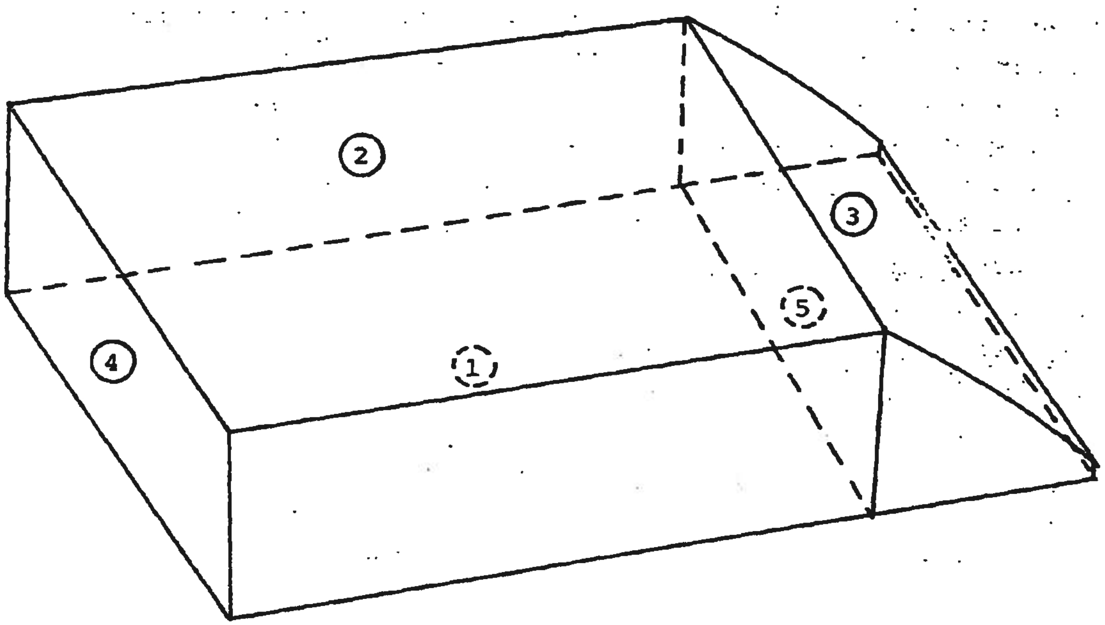
Figure 3.10. Leg-room, seat back top to ceiling and seat top to steering wheel parameter measurement locations in a typical automobile.

The volume was determined by measuring the lengths, breadths, and heights of the desired car cross-section at various points. The cross-section was divided into various simple geometric figures like triangles, squares, and trapezoids according to the characteristics of each individual car (shape of the roof, shape of the windshield and dashboard, etc.). The volume was computed from these various geometric configurations (refer to Figure 3.11).

5. Effective door area--Since different doors open at different angles, this factor was taken into account by determining the actual area that an individual has available to escape. This area was calculated by measuring the perpendicular distance between the door latch on the vehicles and the plane of the door. This perpendicular distance was multiplied by the height of the door opening to obtain the effective door area. (Refer to Figure 3.12.) For four door models, the back as well as front door area was determined.
6. Effective window area--The linear measurements of the window were taken in such a manner as to divide the window into basic geometric shapes and then the window area was computed. Only the window areas which could be used in escaping were considered. (Figure 3.13.)

The above parameter measurements were taken for each of the five automobiles previously tested. See Table 3.8. These measurements were then considered as independent variables in a least squares step-wise multiple linear regression model. Note that the only parameter that could change values within each vehicle was the effective (available for escape) door or window area. The dependent variable was the total escape time for all subjects.

3.1.4.3 A linear regression model: This model can be stated as follows:



DESCRIPTION OF THE PLANES

1 An imaginary plane defined by the lower edge of the windowsill, parallel to the ground

2 Plane of the top of the vehicle

3 Plane defined by the windshield

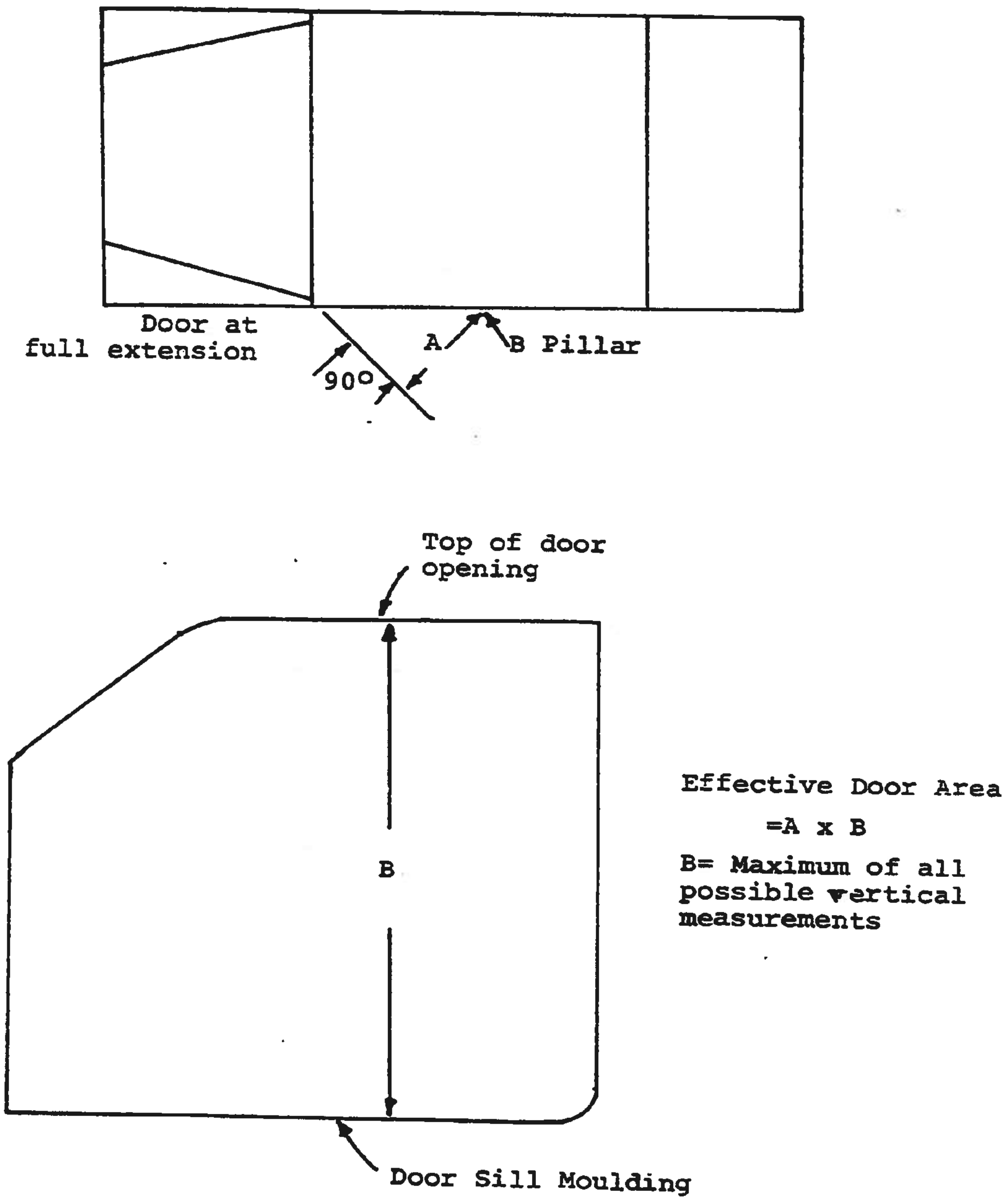
4 An imaginary plane from the back of the back seat which is perpendicular to the ground

5 An imaginary plane parallel to the firewall beginning at the top of the windscreen and running perpendicular to the ground

Figure 3.11. Volume estimate measurement planes for a typical automobile.

EFFECTIVE DOOR AREA MEASUREMENT

Top View of a Vehicle



Door Opening

Figure 3.12. Effective door area measurements in a typical automobile.

TABLE 3.8

TABLE OF THE DESIGN PARAMETERS USED IN THE DEVELOPMENT OF THE PREDICTIVE ESCAPE TIME MODEL

Description of the Parameter	Vehicle				
	1969 Toronado 2 door	1967 Mustang 2 door	1969 V.W. 2 door	1971 Pinto 2 door	1966 Olds 4 door
1. Leg Room (ft)	3.33	3.16	2.00	2.00	3.00
2. Back Top to Ceiling (ft)	.67	1.25	.83	.82	.66
3. Seat Top to Steering Wheel (ft)	.36	.46	.50	.58	.50
4. Volume Estimate (ft^3)	35.68	25.05	24.55	28.56	38.19
5. Effective Door Area (for one door) (ft^2)	11.94	8.13	7.32	10.14	9.32
6. Effective Window Area (for one window) (ft^2)	3.93	3.96	1.85	3.40	1.99

$$T_{ip} = k_{i1} + k_{i2} P_{2p} + k_{i3} P_{3p} + k_{i4} P_{4p} + k_{i5} P_{5p} + k_{i6} P_{6p}$$

where T_{ip} = total escape time for the p^{th} vehicle for the i^{th} condition.

$k_{i1}, k_{i2}, \ldots, k_{i6}$' are constant for the i^{th} condition.

P_{2p} = leg room (includes front and rear) (ft).

P_{3p} = distance between seat back top and ceiling (ft).

P_{4p} = distance between front seat top and steering wheel (ft).

P_{5p} = total volume estimate above the side window sills (ft^3).

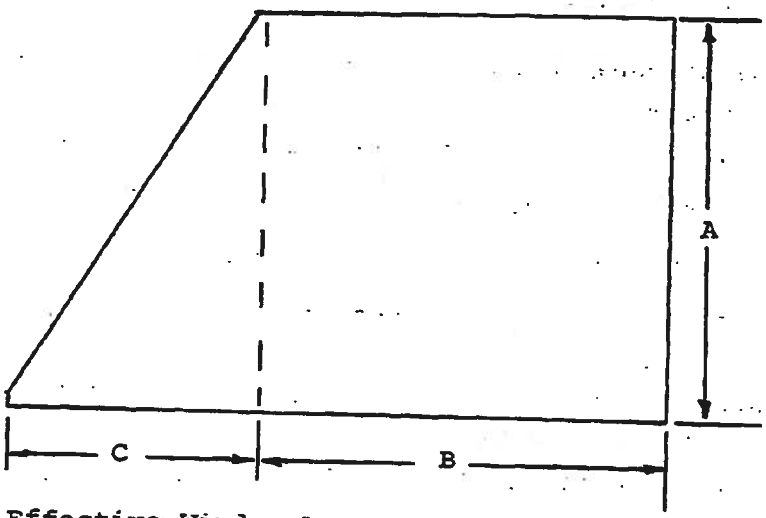
P_{6p} = effective door area or effective window area to the vehicle (ft^2).

The term "condition" above refers to the vehicle passengers involved and is a descriptive parameter. A separate model was constructed for each of the following experimental conditions:

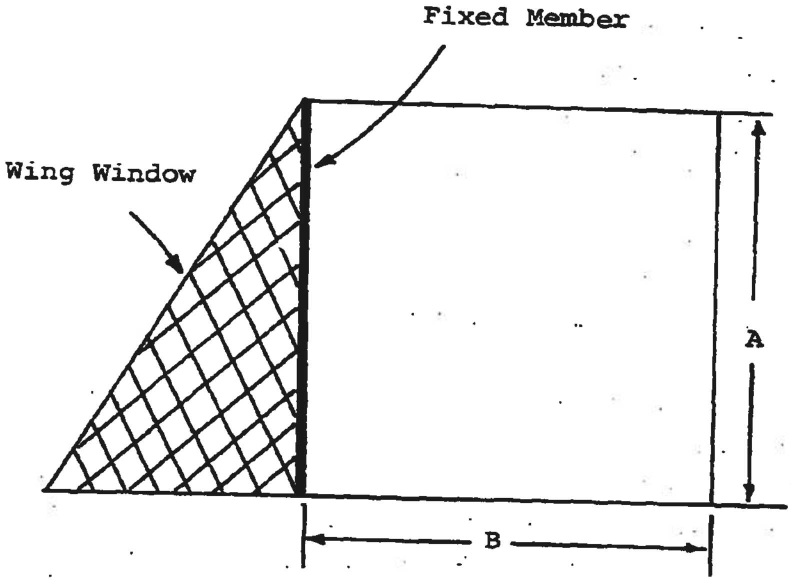
1. All male passenger trials	(100)
2. All female passenger trials	(100)
3. All mixed passenger trials	(100)
4. All younger age group passenger trials	(150)
5. All older age group passenger trials	(150)
6. All injured passenger trials	(150)
7. All not injured passenger trials	(150)
8. All trials	(300)

By utilizing the measurements of the vehicle and the total escape times for each of the 100 trials (5 vehicles x 2 male groups per vehicle x 10 trials per group, with "panic" trials omitted) where all males were involved, for example, it was possible using an IBM 360/50 computer to compute the constraints: $k_{i1}, k_{i2}, k_{i3}, \ldots, k_{i6}$'. These constants are presented in Table 3.9 below.

EFFECTIVE WINDOW AREA CALCULATION



Effective Window Area = A x B + ½A x C



Effective Window Area = A x B

Figure 3.13. Effective window area measurement in a typical automobile.

TABLE 3.9

MODEL CONSTANTS FOR THE PREDICTIVE ESCAPE MODEL

Condition	Description						Multiple Correlation Coefficient R
	k1	k2	k3	k4	k5	k6	
All Trials	3.611	-.44	.347	-3.646	-.01324	-.0187	.940**
Young	2.48	-.24	.249	-2.328	-.0149	-.0146	.938**
Old	4.564	-.604	.418	-4.75	-.012	-.0214	.913**
All Male	1.128	-	-	-.846	-.0071	-.0195	.863**
All Female	6.143	-.806	.617	-6.599	-.0227	-.024	.937**
Mixed	3.422	-.525	.481	-3.124	-.0154	-.0014	.901**
Injured	4.316	-.503	.435	-4.384	-.0157	-.0304	.840*
Non-injured	2.71	-.344	.287	-2.806	-.0113	-.0041	.895**

*Significant at $\alpha < .05$.

**Significant at $\alpha < .01$.

The fit of the regression models to the data is extremely good. Note that it accounts for between 70 and 88 percent (R^2) of the variability in escape time between vehicles and within vehicles (due to changing escape routes) with the model.

3.1.4.3 Verification of the model: The next step was to verify the model using a vehicle that had not been previously used in developing the model, but whose design parameters fell within the range of those used to develop the model. The vehicle selected was a 1971 Chevrolet Vega. Appropriate design parameters for the Vega are:

1.	Leg room	2.58 ft
2.	Back top to ceiling	.75 ft
3.	Seat top to steering wheel	.54 ft
4.	Volume estimate	33.15 ft^3
5.	Effective door area	9.125 ft^2
6.	Effective window area	3.53 ft^2

The parameters above were multiplied by the appropriate constants from Table 3.9 for each condition to obtain a predicted time to escape from the Vega under each condition, assuming that the doors were inoperable or jammed.

The Vega was then instrumented and a full set of experimental trials (except for the "panic" condition) was scheduled for six age-sex groups as with the first five vehicles. Five age-sex groups were run, but, due to conditions beyond the control of the experimental team, the "older-male" group did not participate in the experiment.

Both the empirical and predicted escape times for the "doors jammed" case are given in Table 3.10 below. Note that the percent deviation is reasonably small ranging from -9 percent to +29 percent at the extremes.

Average time for all trials, however, had a deviation of 12.3 percent when two windows were available as

TABLE 3.10

PREDICTED AND ACTUAL TOTAL ESCAPE TIMES FOR A 1971 CHEVROLET VEGA (DOORS JAMMED)

Condition	$T_{predicted}$ (minutes) (2 windows) (1 window)	T_{actual} (minutes) (2 windows) (1 window)	$T_{actual} - T_{predicted}$ (minutes)	% Deviation = $\frac{T_{act} - T_{pred}}{T_{act}}$ X 100
All Trials	0.412	0.470	0.058	12.3
	.487	.524	.037	7.0
Young	.311	.440	.129	29.3
	.363	.450	.087	19.3
Old	.517	.590	.073	14.0
	.593	.621	.028	4.6
All Male	.298	.320	.022	6.9
	.367	.355	-.012	-3.4
All Female	.446	.550	.104	18.9
	.530	.615	.085	13.8
Mixed	.491	.450	-.041	-9.1
	.495	.600	.105	17.5
Injured	.494	.700	.206	29.4
	.600	.770	.170	22.1
Not Injured	.288	.290	.002	0.7
	.303	.326	.023	7.1

escape routes while only a 7 percent deviation was found in the case where one window (driver's window) was available. This result is rather remarkable considering the simplicity of the model. Further, it must be realized that the model was based on the results of empirical escape data on only five automobiles.

Even though the predicted times tended to be consistently lower than the empirically obtained escape times, predicted times tended to be relatively high when actual escape times were high and correspondingly lower when actual escape times were low. The poorest results were obtained in the injury condition. This particular model also had the smallest multiple correlation coefficient (R) when it was derived from the original escape data.

It appears that this model may be useful in distinguishing the relative escape worthiness of passenger cars whose design parameters of interest are within the range of the original five tested. It should be cautioned that the raw numbers obtained from the model (estimated total escape times) are actually expected values of a multivariate distribution with a relatively large variance. Also, the design parameters were only able to account for from 70 percent to 88 percent of the variability in escape times. While the results of the rather simple approach used in deriving the model presented here are certainly encouraging, the model presented must be applied cautiously and should be used as an indicator of possible problems in escape worthiness for passenger cars and not as an indicator of absolute escape times.

3.1.5 Seat Belts--A Possible Escape Problem

3.1.5.1 Introduction: The vehicle escape worthiness studies brought attention to the fact that seat belt assemblies (pelvic and upper torso restraints) were cumbersome and difficult to manipulate especially under conditions of stress (emergency egress). During the test phase for escape worthiness, without exception, subjects criticized the seat belt assemblies and their operation. They made comments such as: "I can't open them very fast," "They are difficult to open sometimes," "It is hard to release someone else's belt when they are injured," "Lap belts should be standardized," "It takes a while to get used to them."

It became apparent that if people have difficulty in the operation of the seat belt assemblies under optimum conditions, such as those depicted in the testing phase, they would certainly have difficulty releasing themselves under more adverse conditions. The seat belt study reported here was directed at testing seat belts under adverse conditions.

The orientation of the vehicle has a direct bearing on an individual's ability to release himself from the seat belt assembly. When the vehicle is in the normal upright position, there is no real obstacle (once one is familiar with hardware operation) in releasing oneself from the restraints. However, the post-crash orientation of a vehicle is other than normal in many cases. When a vehicle comes to rest on its front end, such as may occur when it is diverted to a ditch, and the occupants are restrained by seat belts, the pelvic restraint and the upper torso restraint may be difficult to release even when the occupants are familiar with their operation. In this case the weight of the passengers and/or driver produce a tensile force within the harness system. The operation of the restraints under such circumstances poses special problems in operation of the buckles.

The orientation of the vehicle is related to the amount of tensile stress produced in the webbing. A post-crash vehicle may have come to rest on its top (upside-down). In this case an individual would be held in the seat only by the seat belt assembly.

Three seat positions and four seat belt assemblies, which constitute a representative cross-section of those in use today, were selected for this pilot study. These variables are discussed in the methodology section.

This study represents an attempt to identify, in a very general way, whether a problem exists with respect to a subject's ability to release himself from several types of seat belt assemblies when the subject is oriented so as to place the restraints under unusual tension.

3.1.5.2 <u>Methodology</u>: Included in this section is a discussion of the equipment detailing both the apparatus and the seat belts. The basis for subject selection and the subject description follows. In the experimental design, the independent and dependent variables are outlined. The procedure section details, step by step, the procedure used during the experimentation phase.

(a) <u>Equipment</u>--The front seat of a 1967 Chevrolet Impala was removed from the automobile. It was remounted on a horizontal bar so that it could be rotated to various positions. This seat was selected since it was of the most basic form (no bucket seats, no arm rests, etc.). A ten foot steel bar was mounted to the rear brackets on the under side of the seat. Each end of the bar was mounted to platforms that were five feet off the ground. The seat could then be rotated freely, and the seat could be placed at any angle in the vertical plane of the longitudinal axis of the hypothetical automobile. (See Figure 3.14.)

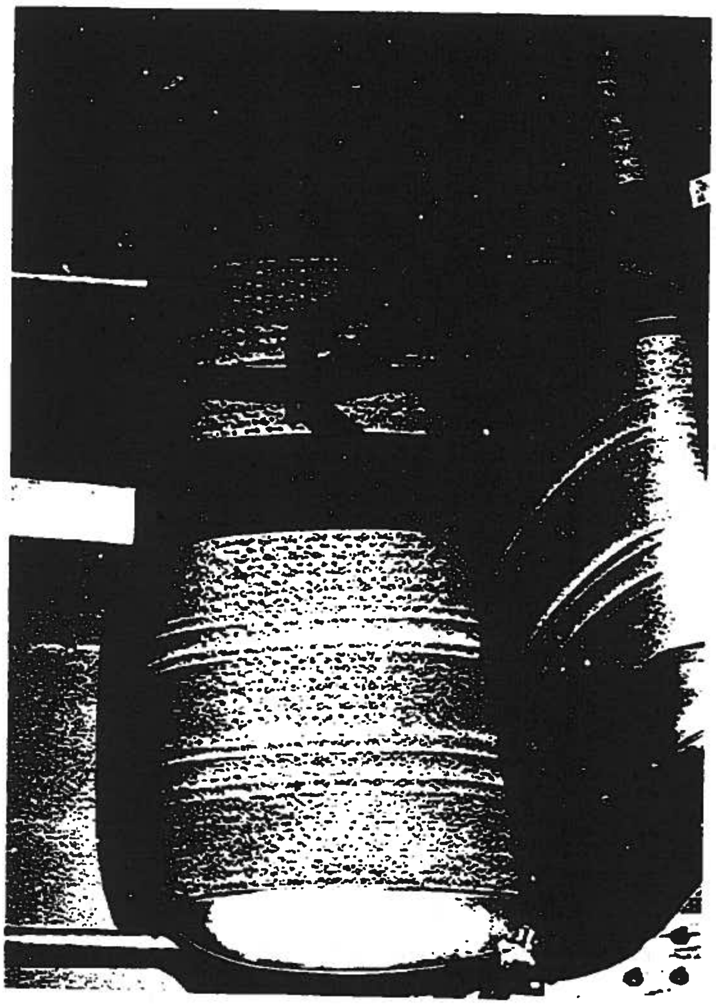


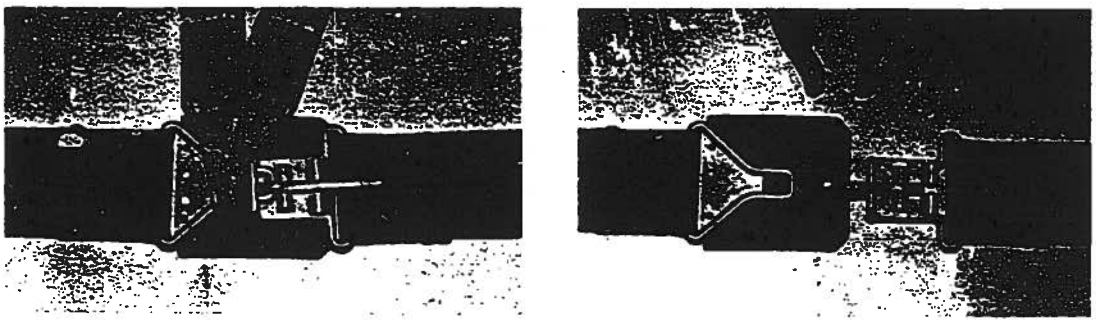
Figure 3.14. Experimental apparatus.

The positions of the seat were controlled manually. The seat with subject was placed in position manually. The seat could be locked in place once it had been rotated to a desired angle.

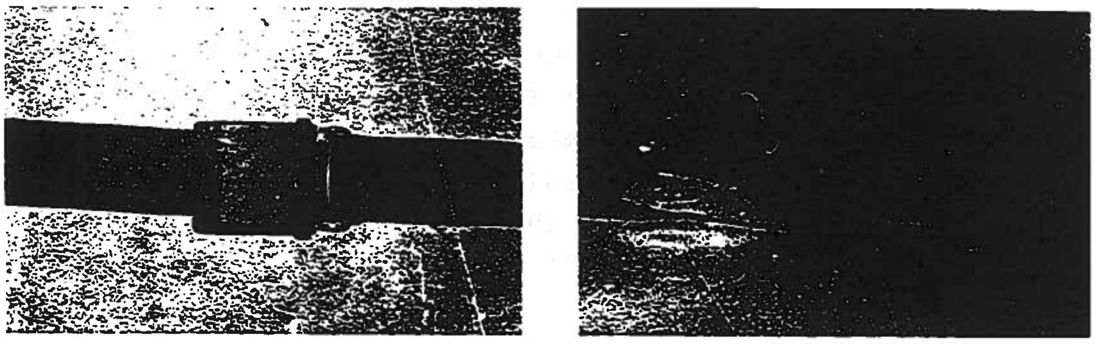
Four different types of seat belt assemblies were tested. Each had a pelvic restraint and upper torso restraint. The restraints were installed so that the subject would sit in the middle of the seat. The upper-torso restraint was fixed to a position which simulated an actual position. The assemblies were easily interchangeable. All seat belt assemblies were of type 2 (combination of pelvic and upper torso restraints) as outlined in Motor Vehicle Safety Standard No. 209--Docket No. 69-23.

Assembly (seat belt assembly) number one is the type used in some sport cars and in racing cars. It has a belt for each shoulder attached directly behind the head and to the buckle on the pelvic restraint. By pulling the lever on the buckle, both the restraints are released. (See Figure 3.15.)

Assembly number three is operated similarly to number two except that both restraints are connected to one lever action buckle. Both belts are released when the buckle is activated; however, both restraints are permanently connected on the lower end. (See Figure 3.16.)

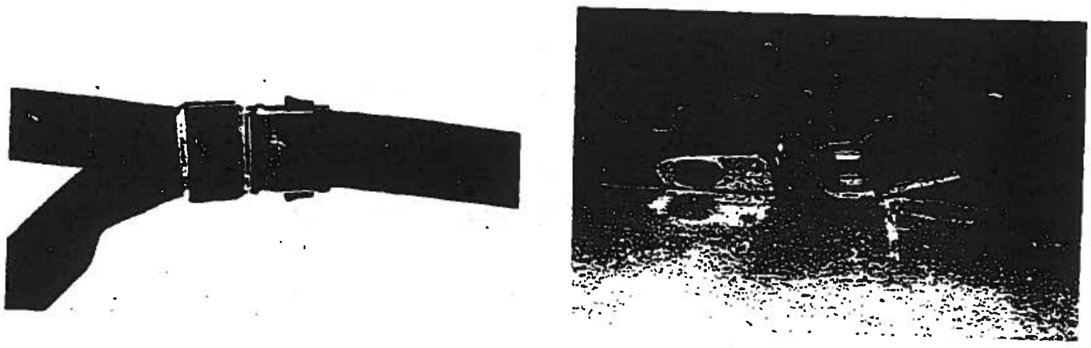


Buckle on seat belt assembly one--locked and exploded view.

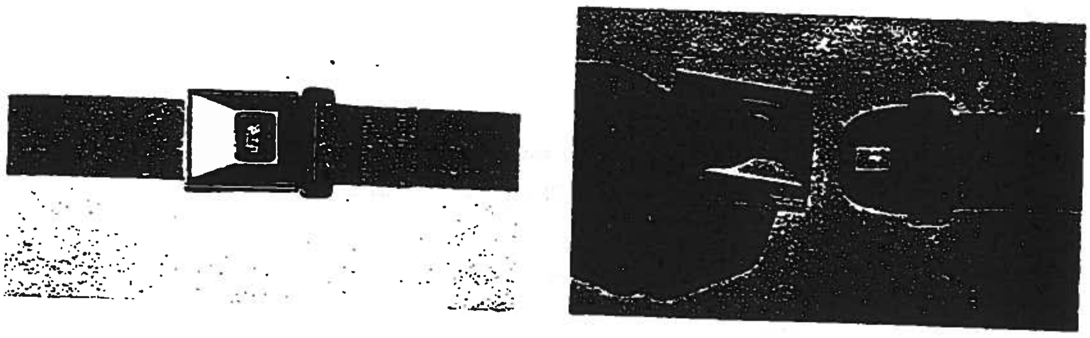


Buckle on seat belt assembly two--locked and exploded view.

Figure 3.15. Buckles on seat belt assemblies one and two.



Buckle on seat belt assembly three--locked and exploded view.



Buckle on seat belt assembly four--locked and exploded view.

Figure 3.16. Buckles on seat belt assemblies three and four.

Each restraint of assembly number four is connected separately by means of a pushbutton-type buckle. (See Figure 3.16.)

(b) Subjects--Due to obvious dangers involved in releasing oneself from seat restraints while in an upside-down position, it was necessary to select subjects who were athletically inclined and could more easily adapt to this situation. Two males were selected who were intercollegiate lettermen in gymnastics. One female was selected that had an athletic background.

Age, weight and height of the subjects were as follows:

		Age	Weight	Height
Male	1	25	165	6'
Male	2	22	150	5'7"
Female	3	28	128	5'6"

(c) Experimental design--

(1) Independent variables--There were three independent variables. They were subject (3), seat angle (3), and seat belt (4). The subject cross-section was two males and one female (see subject section). The seat had three positions and these are denoted by the angle that the seat back made with its normal vertical position. In position A (see Figure 3.17a), the seat back was horizontal ($\theta = 90^\circ$). In position B (see Figure 3.17b), the seat back was placed at 135° angle to the vertical position. In position C (see Figure 3.17c), the seat back was at 180° to its vertical position.

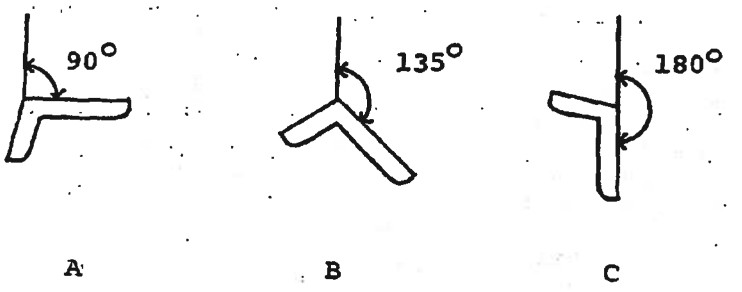


Figure 3.17. Seat orientation for the seat belt assembly escape study.

The main independent variable was seat belt assembly. Each was described in detail in the equipment section. They will be referenced as assembly (seat belt assembly) one, assembly two, assembly three, and assembly four.

(2) Dependent variable--The dependent variable was elapsed time. It was measured from the time the subject was told to begin (by the verbal command "go") his escape from the restraints, to the time he had completely released himself or was free from the restraints. The elapsed time was measured to the nearest tenth of a second.

(d) Procedure--The testing was conducted during the course of one day. The subjects were given the following instructions as a group:

> You will be strapped in this automobile seat by use of various types of seat belt assemblies. Once you have adjusted the seat belts and buckled them to accommodate your individual size and shape, please notify me and I will check the adjustment.

> At this time the seat will be rotated to one of three positions. In each of these three positions you will be supported entirely by the restraints. Once the seat has been locked in position you will be told "go." Upon hearing this verbal command, begin at once to release yourself from the restraints. It will take from two to five seconds to rotate and lock the seat in position. Make no preparation to release until told "go." I want to impress on you the importance of escaping just as quickly as possible. Expediency is of the utmost importance. Are there any questions?

At this time the first subject was asked to take his place in the seat. The seat was in its normal upright position. An experimenter aided the subject in adjustment of the restraints to insure uniformity of fit for all subjects. The subject was placed into an escape position upon his command. By allowing the subject to select his own timing, maximum effort could be derived from each subject. As soon as the rotation of the seat stopped and the chair was locked in position (from 2 to 5 seconds) the subject was told "go."

A stop watch for measuring time to escape was started when the subject was told "go" and stopped when he was completely free of the restraints. This elapsed time was the dependent variable.

One subject was tested every four minutes. Since there were three subjects, each subject had eight minutes to rest and recuperate between trials. Testing was continuous throughout the afternoon since subjects had sufficient interim rest periods.

3.1.5.3 Results:

(a) Introduction--For clarity of analysis this section is divided into two parts. The first part deals directly with a quantitative assessment of the experiment, and the second part depicts a qualitative assessment, as well as conclusions and recommendations.

(b) Quantitative results--Upon inspecting the relative values of the mean time to escape for the different assemblies, it becomes readily apparent that the mean for assembly four is much greater. The means are respectively 1.20, 1.75, 2.67, 5.69 seconds. Since the primary objective of the experiment was to isolate those seat belts which proved particularly hazardous, the data for assembly four was examined separately so that it could be compared to others. Using a "t" statistic, a 98 percent confidence interval was computed to determine if the escape times for assembly four were significantly greater than those of the other assemblies. The 98 percent confidence interval for time to elapse was:

$$2.81 \le \mu_4 \le 8.55$$

The means of the other three assemblies were all below the above interval. It can then be concluded that the mean time of assembly four is significantly greater than the mean times of the others at the $\alpha = .02$ level.

Figure 3.18 depicts the data graphically. In all seat positions the mean times

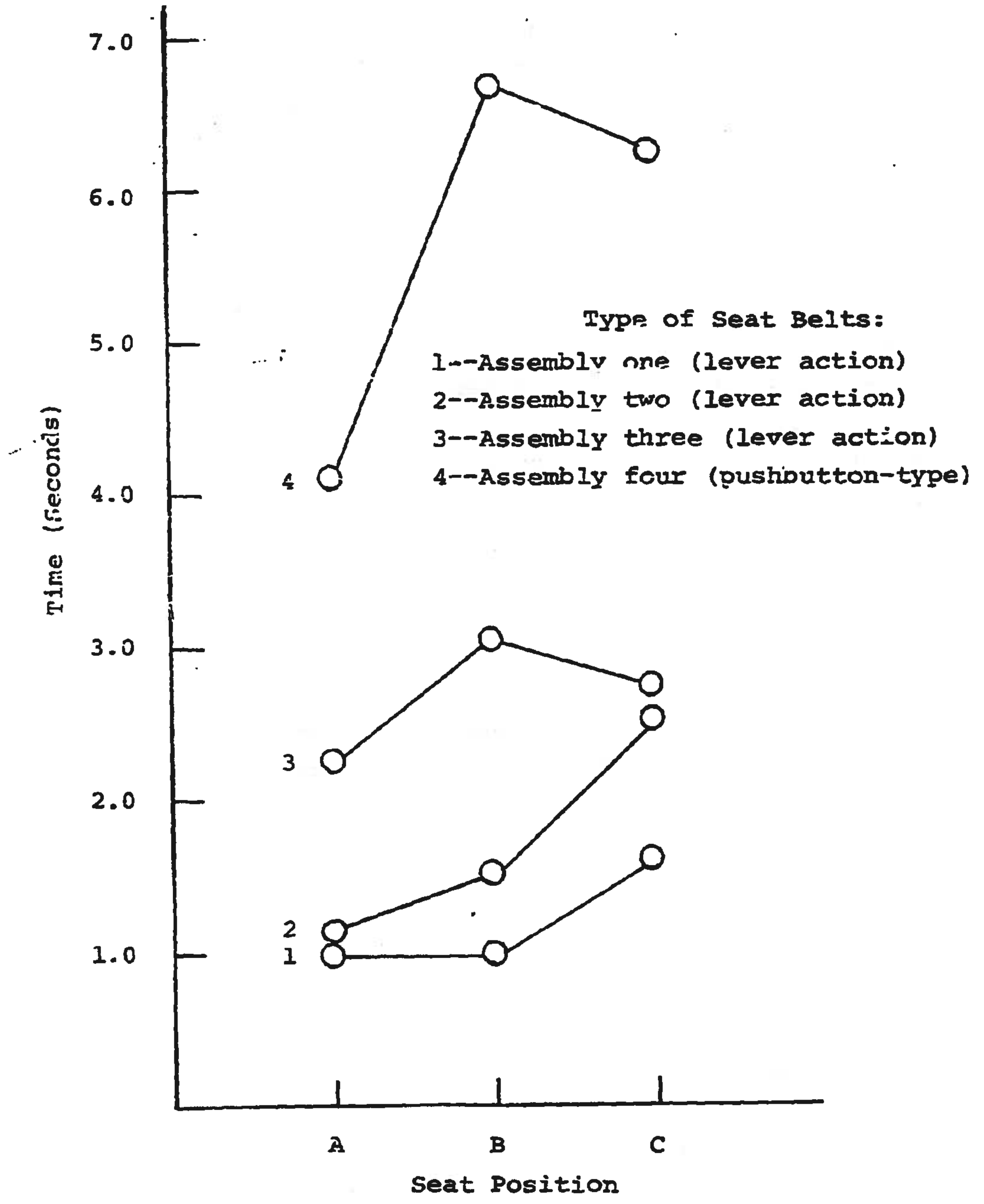


Figure 3.18. Time versus seat position for various types of seat belts.

to escape are ordered for the individual seat belts. That is, assembly one has the lowest times in all seat positions, assembly two the next, etc. (See Table 3.11.) There is not a statistically significant difference in escape times between assembly one, two, and three, however.

Figure 3.19 shows the comparative mean times for male versus female subjects. For assemblies one, two, and three, the female mean times were not only comparable to the male escape times but slightly lower. However, the female experienced considerable difficulty in escape from the restraint of assembly four. The males also experienced greater difficulty but not to such a degree. This is perhaps best explained by the fact that assemblies one, two, and three were not so dependent on the subject's strength as was assembly four. This dependence on strength is obviously not a desirable one under the prevailing experimental circumstances.

(c) Qualitative results--The data provided above provide a basis for questioning the operation of certain buckles. There are other less qualitative measures that lend further support to this contention. The subjects, without exception, disliked assembly four when confronted with releasing themselves from the restraints while being suspended by them. The subjects made comments such as:

1. "I can't get my fingers under the belt so that I can get leverage."

TABLE 3.11

MARGINAL MEANS FOR MAIN FACTORS--SEAT BELT STUDY (IN SECONDS)

Type of Seat Belt	Seat Position			Seat Belt Means
	A	B	C	
Assembly one	1.00	1.00	1.60	1.20
Assembly two	1.17	1.53	2.56	1.75
Assembly three	2.16	3.67	2.76	2.66
Assembly four	4.10	6.70	6.26	5.69
Seat Position Means	2.18	3.08	3.29	
Overall Mean				2.83

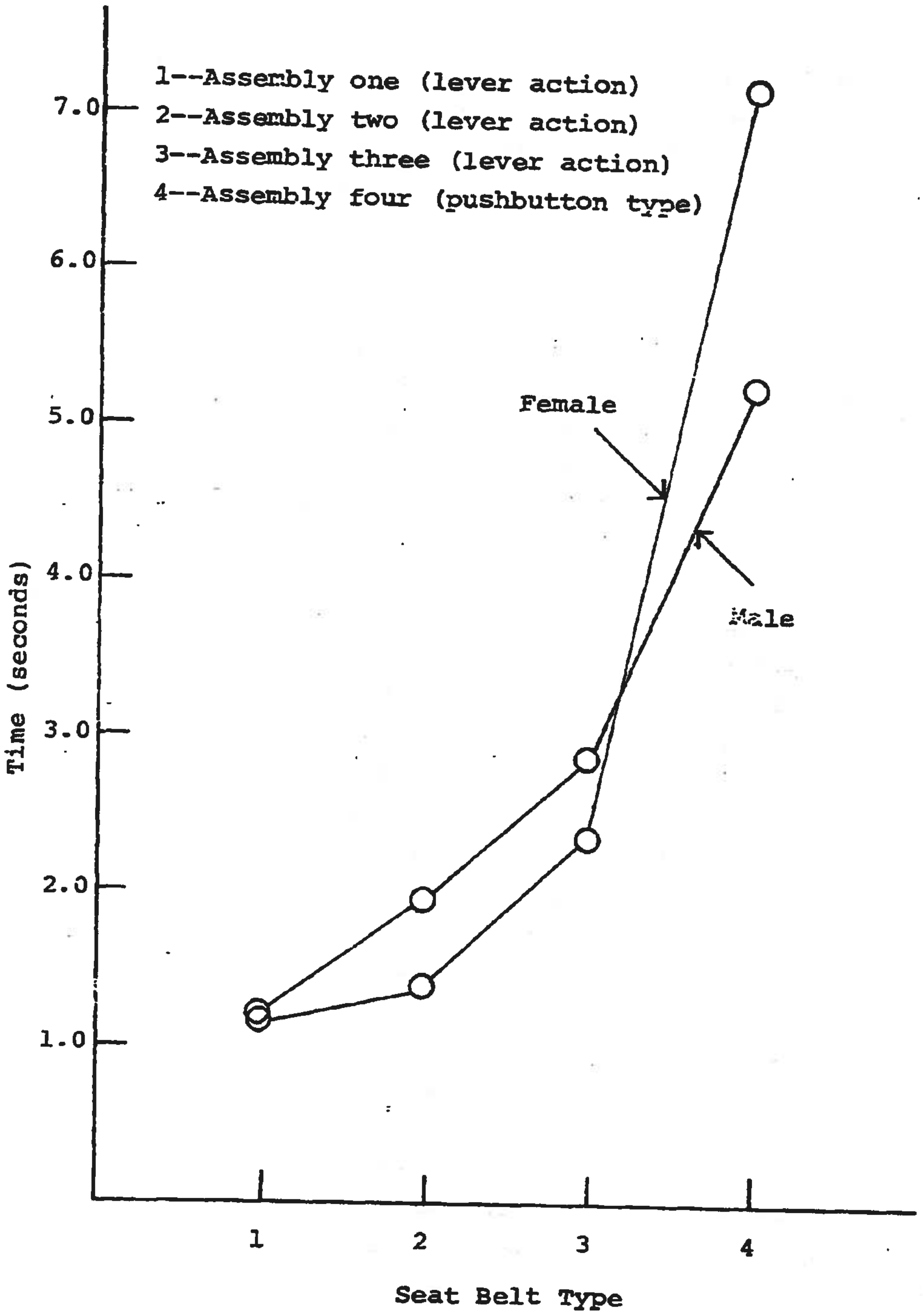


Figure 3.19. Time versus seat belt type for subject sex.

2. "A person that is not in peak physical condition would have a hard time getting out."
3. "A person could not stay that way (suspended by restraints) very long without passing out."
4. "There has got to be a better way than pushing that button."

The seat positions were merely representative of those positions which would suspend a person by the pelvic and upper torso restraints. The study was not designed to draw definite conclusions about these positions. However, the variation in escape times between the positions can be easily explained. The difficulty in escape for positions B and C can be attributed to the distribution of force in the belt rather than awkwardness of body orientation. The mean times for seat positions A, B, and C were respectively 2.18, 3.08 and 3.29 sec. It appears that in seat position A the body is held in position by both the pelvic restraint and the upper torso restraint. In seat positions B and C the pelvic restraint essentially suspends the entire body while the shoulder strap hangs without function. Therefore, greater tension occurs in the pelvic restraint in positions B and C and we might expect longer release times due to a concentration of weight on the buckle of the pelvic restraint. There were no comments to the effect that one seat position was more awkward than the other.

It is readily apparent that hardware of a seat belt assembly, that is difficult to operate when the subject is suspended, creates a potentially hazardous situation during a post-crash emergency where the vehicle is in some degree inverted. A person's inability or ability to remove himself from his seat belts may be the difference between life and death. Of the assemblies tested, assembly one with the pushbutton-type buckle is by far the most hazardous as far as escape during vehicle inversion is concerned. Many automobiles are supplied with this type of buckle. Of the other seat belt assemblies tested (lever action buckle), there were no definite problems. The escape times were not inordinately long nor were the forces required to effect their release unusual.

The pushbutton type buckle used in this experiment was tested against the buckle release specifications set forth in Motor Vehicle Safety Standard No. 209--Section S4.3 (d)(1). This standard states that the "...seat belt assembly shall release when a force of not more than 30 pounds or 14 kilograms is applied." The method prescribed in Section S5.2 (d)(1) (with amendments) was used to test the pushbutton type buckle in question for compliance with standards. This buckle was well within tolerance, requiring a maximum of 29 pounds force to activate the mechanism for a situation where a simulated 95th percentile male is restrained in an inverted position.

The above results suggest that the current standards regarding seat belt release forces should be reviewed and altered based on strength capabilities of individuals in the seat.

3.1.6 Conclusions and Recommendations

Analysis of the quantitative data combined with qualitative results of the studies described in this section are a basis for the following conclusions:

1. Egress time under emergency conditions differed widely among the vehicles tested. A Volkswagen "Beetle" was consistently poorer than the other vehicles tested for escape worthiness.
2. Passenger car interior vehicle design parameters appear to be extremely important in affecting escape time.
3. The empirically based linear regression model developed in this study appears to be valid for predicting at least relative escape worthiness of passenger cars, based on vehicle interior design parameters.
4. The older group of subjects (39-59 years) took a significantly longer time to escape from the vehicles than younger (19-29 years) subjects.
5. Time to escape from a passenger car is significantly higher when doors are jammed than when they are not.
6. Injury to one of the passengers (simulated unconsciousness) increases escape time markedly over similar situations where no one was injured.
7. Female and mixed sex subject groups took longer on the average to facilitate egress from the vehicle than the male groups.
8. Darkness did not appear to adversely affect escape time for younger subjects (19-29 years) in this experiment.
9. Certain lap belt and shoulder harness unlocking mechanisms may be difficult or impossible to operate when the belt is under tension. This can occur when the vehicle has rolled and the subject is suspended in his lap belt.

On the basis of the studies contained herein, the following recommendations are made:

1. Attempts should be made to standardize the operation and general location of door handles, window cranks, door locks, front seat back latches and shoulder and lap belt locking mechanisms.
2. The design of future passenger car interiors should consider the problem of egress under emergency conditions. The model presented in Section 3.1.4 can provide insights into the investigation of the problem.
3. Information should be disseminated to encourage the public to familiarize themselves with the operation of doors, windows, etc., when riding in vehicles unfamiliar to them.
4. Current standards (Standard 209, Section S4.3 (d)(1)) regarding seat belt release forces for pushbutton type seat belt buckle assemblies should be reviewed. Modifications to this standard should be based on appropriate strength capabilities of individuals in the seat belt user population.

3.2 PASSENGER VEHICLE SUBMERGENCE

3.2.1 Introduction

From the conclusions reached in the first year's contractual effort under DOT Contract No. FH-11-7303 and reported in the final report (1) the following areas of further research effort were recommended in the section on passenger vehicle submergence:

1. Manned vehicle submergence tests.
2. Scale model, water-entry tests to determine entry dynamics phenomena.
3. Extension of the Engineering Analysis of the vehicle water-entry process.
4. Unmanned, full-scale vehicle submergence tests at zero entry velocities to determine sinking rate and sinking dynamics.
5. Unmanned, full-scale dynamic vehicle submergence tests at different entry angles, entry velocities and heights above water.
6. Tests to determine the feasibility of methods to improve the passenger and luggage compartment air-tight integrity by the use of sealing techniques, built-in flotation gear, and deployable flotation gear.

When the priorities were established for conducting further research to be performed under contract FH-11-7512, it was found that a balanced escape worthiness program based on the funds available would not permit all of the areas listed above to be researched. The decision was then made to pursue three major research areas as having the most promise of providing the data needed by NHTSA.

A list of these areas and the reason for its selection follows:

1. Extension of the engineering analysis of the vehicle water entry process to develop a more sophisticated, computerized predictive model. This area was chosen because of the need to further understand the dynamics of submergence prior to undertaking any additional full-scale or scale model tests of vehicle water entry dynamics.
2. Dry-land, full-scale vehicle air leak-rate experiments to predict vehicle water leak-rates. This area was chosen for study because of the need for a non-destructive test to use in evaluating vehicle water-leak rates.
3. Determination of vehicle flotation volumes for typical passenger vehicles in order to predict vehicle sinking times. It was found that data on vehicle flotation volumes was not available from any manufacturer, so that a feasible method had to be developed for making such measurements.
4. Vehicle sinking time analyses, utilizing the information developed in (2) and (3) above. Such predictions are an inherent part of evaluating escape worthiness.

This section on passenger vehicle submergence will present the contractual effort in these areas. It has been organized as follows:

3.2.1 Introduction.
3.2.2 Vehicle Entry Dynamics--Predictive Computerized Model.
3.2.3 Dry-Land Vehicle Air Leak-Rate Simulation and Correlation Studies.
3.2.4 Predicted Vehicle Characteristic Sinking Times for the 1967 Chevrolet Impala, the 1971 Ford Pinto and the 1970 American Motors Hornet.
3.2.5 Measurement of Vehicle Flotation Volumes.

3.2.6 General Discussion.

3.2.7 General Conclusions and Recommendations.

The theoretical analyses supporting the tests performed in Sections 3.2.3, 3.2.4, and 3.2.5 above are presented in Appendices C-2 through C-4 in this report. In addition, the computer program documentation, listings, and test cases of the computer programs developed are also presented in Appendix C-1.

3.2.2 Vehicle Water-Entry Dynamics--Predictive Computerized Model

The initial effort to model entry dynamics was reported in Appendix D of the final report on Contract FH-11-7303 (1). That effort resulted in the development of a second order, non-linear differential equation describing the dynamics of a vehicle entering the surface of a body of water. The key simplifying assumptions made in the analysis were:

1. All flow processes are quasi-steady. (The unsteady flow effects due to the initial vehicle water-entry process were ignored.)
2. A characteristic "bluff-body" drag coefficient of 1.0 is assumed for the complete water-entry process.

<u>3.2.2.1 Development of quasi-steady vehicle water-entry program "B" based upon constant vehicle drag coefficient</u>: The resulting equation which was developed previously is

$$\frac{W}{g}\frac{d^2s}{dt^2} = -K_D\left[\frac{ds}{dt}\right]^2 - K_B(s)\sin\phi_e + W\sin\phi_e$$

which describes the displacement (s) of the vehicle with time along a given entry path measured at an angle ϕ_e from the horizontal. Here W is the vehicle weight and

K_D and K_B are constants depending on the assumed drag characteristics and buoyancy characteristics respectively of a given vehicle.

Specifically:

$$K_D = \frac{C_D \rho_{H_2O} A_c}{2g}$$

where C_D = 1.0 (Bluff-body drag coefficient)

ρ_{H_2O} = specific weight of water (lbf/ft^3)

A_c = vehicle characteristic frontal area (ft^2)

$K_B = \frac{F_B}{\ell_s} = \frac{\text{Buoyancy Force}}{\text{Vehicle Length}}$

with $F_B = V_s \rho_{H_2O}$

and V_s = vehicle displacement volume

The above non-linear differential equation was programmed for numerical integration using the fourth-order Runge-Kutta method (see Appendix C-1 for this program documentation). The test case chosen in Appendix C-1 was run off and was found to check closely the vehicle dynamics of the earlier hand calculations.

Subsequently, an ordered vehicle water-entry study was made on the computer employing the vehicle constants K_D, K_B, and W, derived from the vehicles used in the earlier 1961 Michigan submergence experiments reported by Kuhn.* The results of that study are displayed as a 4 x 4 matrix of the vehicle initial entry conditions (entry velocity, V_e, and entry angle, ϕ_e) for the following values:

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*A portion of the summary of this report appears in Reference (1).

$$V_e = 25, 45, 65, 88 \text{ ft/sec}$$
$$\phi_e = 30^\circ, 45^\circ, 60^\circ, 90^\circ$$

Matrix summaries were prepared from data for the four vehicles tested in the 1961 Michigan submergence tests:

1. 1961 Ford 2-door sedan.
2. 1961 Chevrolet 4-door sedan.
3. 1954 Ford station wagon.
4. 1953 Rambler compact.

The results are shown in Tables 3.12 through 3.15 where the vehicle dynamics are presented in terms of the following parameters:

G_{max} = the maximum deceleration in g's (deceleration (ft/sec^2)/32.174)

S_{max} = the maximum distance the leading edge of the vehicle passes along the path of motion measured from the surface of the water.

t_{max} = the elapsed time (after vehicle entry) required for the vehicle velocity to be reduced to zero.

It is interesting to note that the maximum g's and the maximum submergence distances are predicted for the case of the minimum entry angle (30°) and the highest entry velocity (88 ft/sec). It is not surprising that the maximum g's occur at the highest entry velocity inasmuch as the hydrodynamic drag depends upon the square of the velocity. However, the maximum submergence distances predicted for all four vehicles (occurring at the minimum entry angle) are the result of the reduced vertical component of the deceleration force due to buoyancy acting at the lower entry angles.

Of further interest is the range of G_{max} occurring for all four vehicles at the highest entry velocity studied (88 ft/sec) at the minimum entry angle of 30°. The values range from 36.39 g's for the 1961 2-door Ford to 50.89 g's

TABLE 3.12

WATER ENTRY SUMMARY
1961 FORD 2-DOOR SEDAN
COMPUTER PROGRAM "B"
DRAG COEFFICIENT = 1.0

V_e Φ_e	30°			45°			60°			90°		
	G_{max}	S_{max}	t_{max}	G_{max}	S_{max}	t_{max}	G_{max}	S_{max}	t_{max}	G_{max}	S_{max}	t_{max}
25 fps 17 mph	2.47	12.79	1.63	2.27	12.53	1.45	2.11	12.40	1.34	1.98	12.31	1.28
45 fps 37 mph	9.15	14.08	1.35	8.94	13.63	1.20	8.78	13.39	1.12	8.65	13.24	1.07
65 fps 44 mph	19.62	15.20	1.21	19.42	14.65	1.07	19.26	14.34	1.00	19.12	14.14	0.95
88 fps 60 mph	36.39	16.29	1.11	36.18	15.65	0.98	36.02	15.30	0.91	35.89	15.06	0.87

Φ_e = Entry angle in degrees

V_e = Entry velocity in feet per second

G_{max} = Maximum deceleration in g's

S_{max} = Total distance submerged in feet (at V = 0)

t_{max} = Elapsed time in seconds corresponding to S_{max}

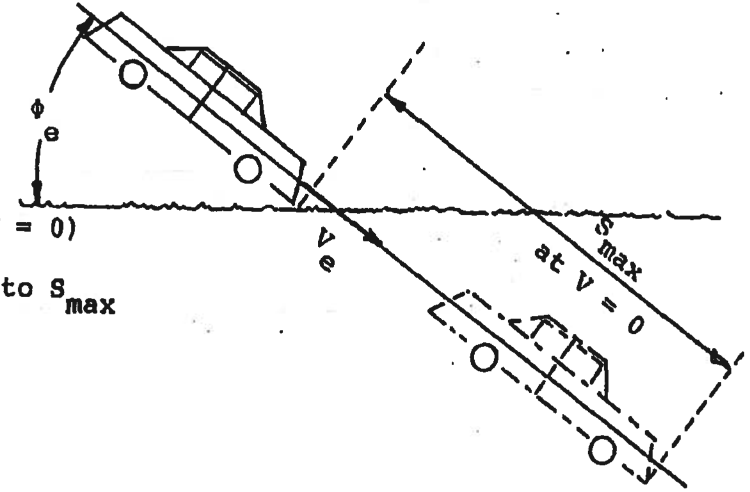


TABLE 3.13

WATER ENTRY SUMMARY
1961 CHEVROLET 4-DOOR SEDAN
COMPUTER PROGRAM "B"
DRAG COEFFICIENT = 1.0

V_e ϕ_e	30°			45°			60°			90°		
	G_{max}	S_{max}	t_{max}	G_{max}	S_{max}	t_{max}	G_{max}	S_{max}	t_{max}	G_{max}	S_{max}	t_{max}
25 fps 17 mph	2.71	12.14	1.59	2.50	11.89	1.41	2.34	11.77	1.31	2.21	11.69	1.24
45 fps 37 mph	9.89	13.34	1.32	9.69	12.93	1.18	9.53	12.71	1.10	9.39	12.56	1.04
65 fps 44 mph	21.18	14.39	1.18	20.98	13.87	1.05	20.82	13.59	0.98	20.68	13.40	0.93
88 fps 60 mph	39.24	15.40	1.08	39.04	14.81	0.96	38.88	14.48	0.89	38.74	14.26	0.85

TABLE 3.14

WATER ENTRY SUMMARY
1954 FORD STATION WAGON
COMPUTER PROGRAM "B"
DRAG COEFFICIENT = 1.0

V_e Φ_e	30°			45°			60°			90°		
	G_{max}	S_{max}	t_{max}	G_{max}	S_{max}	t_{max}	G_{max}	S_{max}	t_{max}	G_{max}	S_{max}	t_{max}
25 fps 17 mph	3.65	10.20	1.50	3.44	10.00	1.33	3.28	9.92	1.23	3.15	9.86	1.17
45 fps 37 mph	12.94	11.14	1.24	12.73	10.81	1.10	12.57	10.64	1.03	12.44	10.53	0.98
65 fps 44 mph	27.54	11.95	1.10	27.33	11.55	0.98	27.17	11.33	0.91	27.04	11.18	0.87
88 fps 60 mph	50.89	12.74	1.01	50.68	12.28	0.89	50.52	12.02	0.83	50.39	11.85	0.79

TABLE 3.15

WATER ENTRY SUMMARY
1953 RAMBLER
COMPUTER PROGRAM "B"
DRAG COEFFICIENT = 1.0

V_e ϕ_e	30°			45°			60°			90°		
	G_{max}	S_{max}	t_{max}	G_{max}	S_{max}	t_{max}	G_{max}	S_{max}	t_{max}	G_{max}	S_{max}	t_{max}
25 fps 17 mph	3.56	9.37	1.28	3.36	9.14	1.14	3.20	9.02	1.06	3.06	8.94	1.01
45 fps 37 mph	12.66	10.47	1.07	12.46	10.10	0.95	12.30	9.90	0.88	12.16	9.77	0.84
65 fps 44 mph	26.96	11.38	0.96	26.76	10.93	0.85	26.60	10.69	0.79	26.46	10.51	0.75
88 fps 60 mph	49.84	12.23	0.89	49.63	11.73	0.78	49.47	11.45	0.72	49.34	11.26	0.69

for the 1954 Ford station wagon. The higher values of both the drag constant, K_D, and the buoyancy constant, K_B, for the 1954 Ford station wagon are the primary reasons for this result. In general, it can be said that vehicles with large frontal areas, large flotation volumes, and low weight would exhibit large deceleration forces, while vehicles with small frontal areas, small flotation volumes and large weight would experience lower deceleration forces.

Also of interest is the relative insensitivity of S_{max} and t_{max} to either entry velocity at a given entry angle or entry angle at a given velocity.

It is of interest also to show the time-history of the vehicle dynamics for the case of one entry velocity and entry angle for the four vehicles. Figures 3.20 through 3.23 show the variation of the vehicle velocity, the vehicle penetration distance and the vehicle deceleration force in g's as a function of time. The initial conditions chosen for the figures are:

$$V_e = 25 \text{ ft/sec}$$

$$\phi_e = 45^\circ$$

These conditions represent most closely the actual conditions employed in the 1961 Michigan submergence tests employing these four types of vehicles.

In general, the curves show a monotonically decreasing velocity and increasing penetration distance for all four vehicles up to t_{max} where the vehicle velocity is zero. The deceleration force of similar magnitude for all four vehicles is seen to maximize instantaneously at $t = 0$ (time of initial water-entry) at about 2 to 3 g's and to decrease very rapidly to very low values for most of the entry process. It would seem that this result is unrealistic

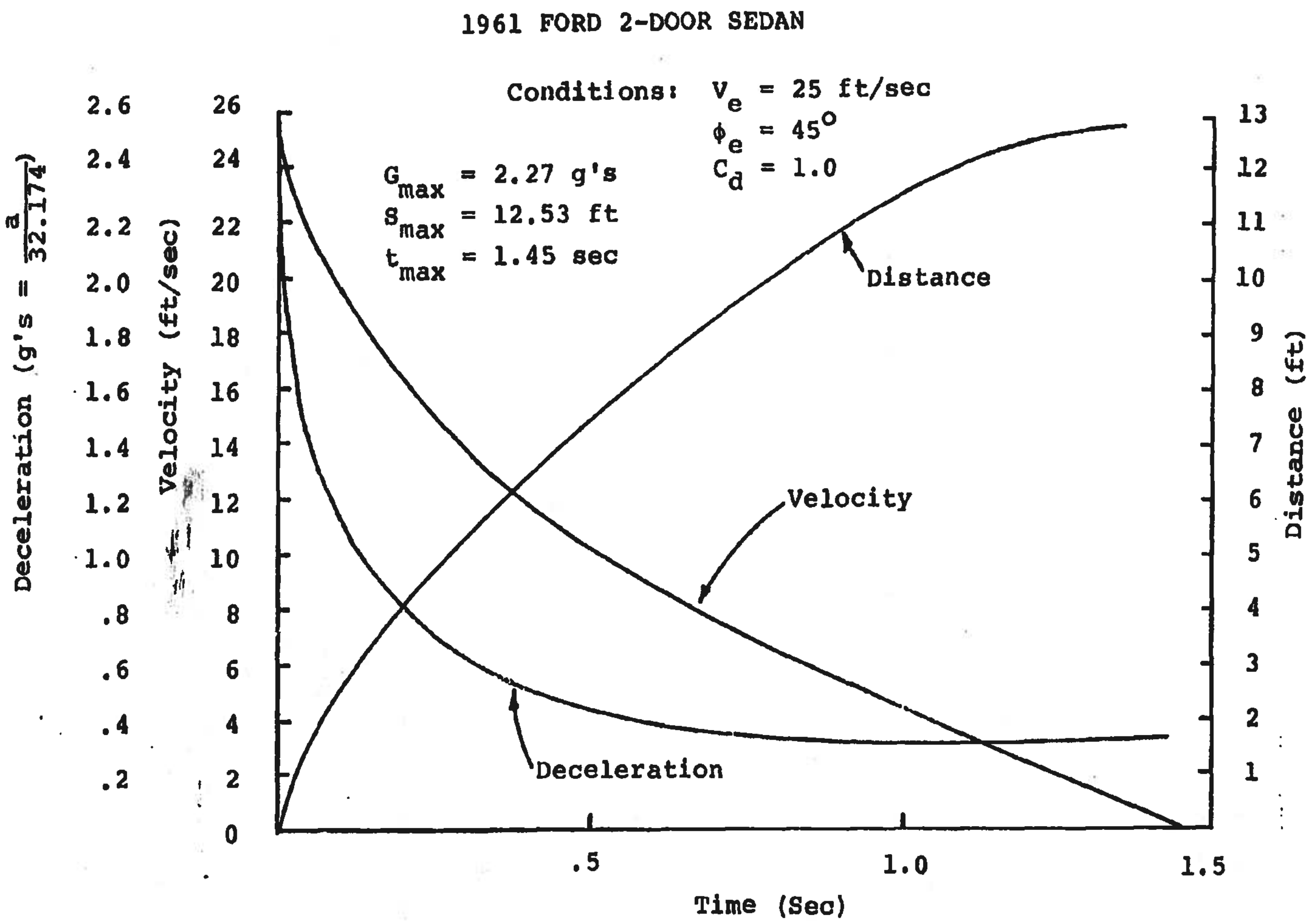


Figure 3.20. Deceleration, velocity and penetration distance for a 1961 Ford 2-door sedan upon entry into a body of water for the conditions shown. (Computerized Predictive Model--Program "B")

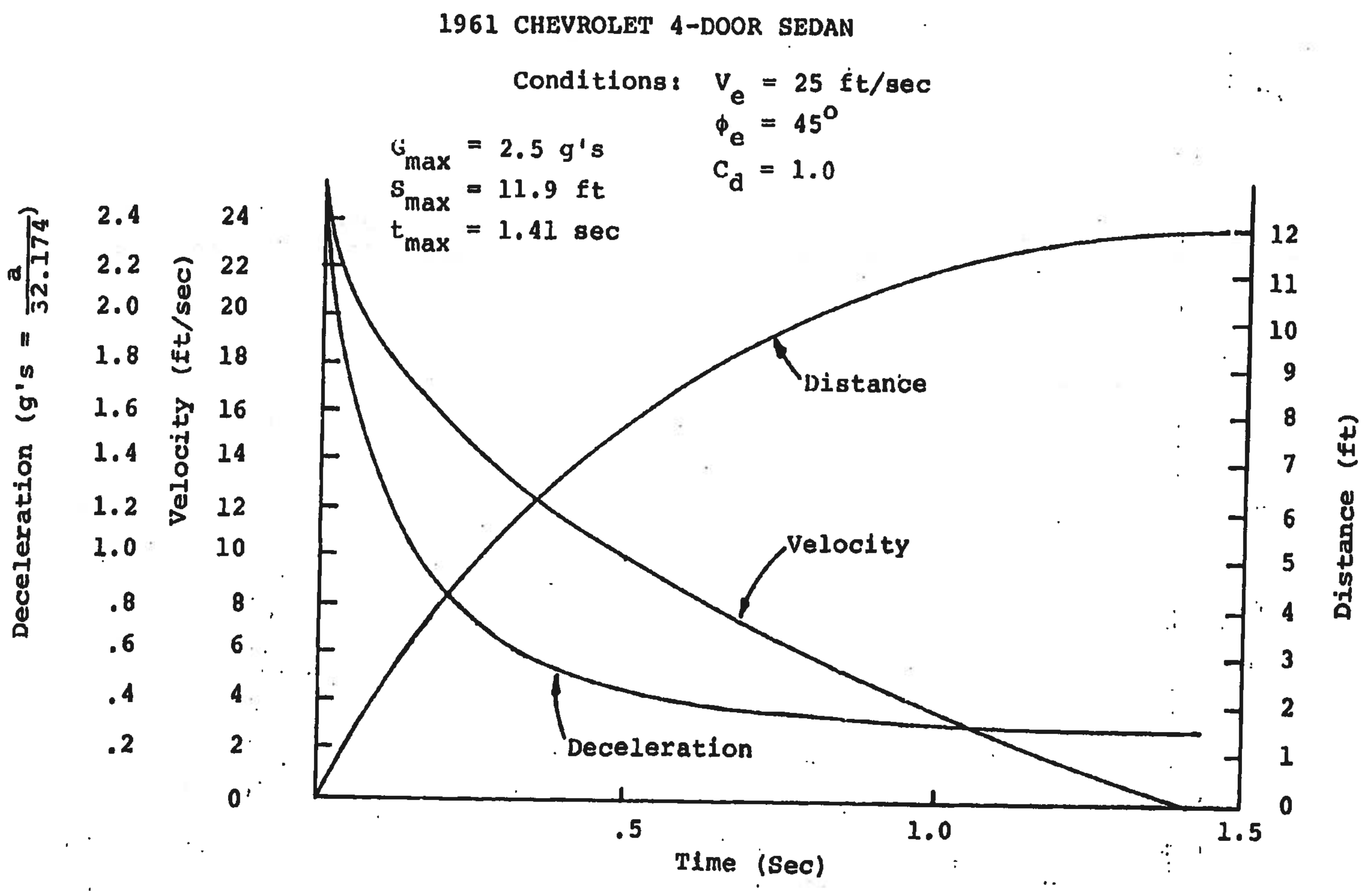


Figure 3.21. Deceleration, velocity and penetration distance for a 1961 Chevrolet 4-door sedan upon entry into a body of water for the condition shown. (Computerized Predictive Model--Program "B")

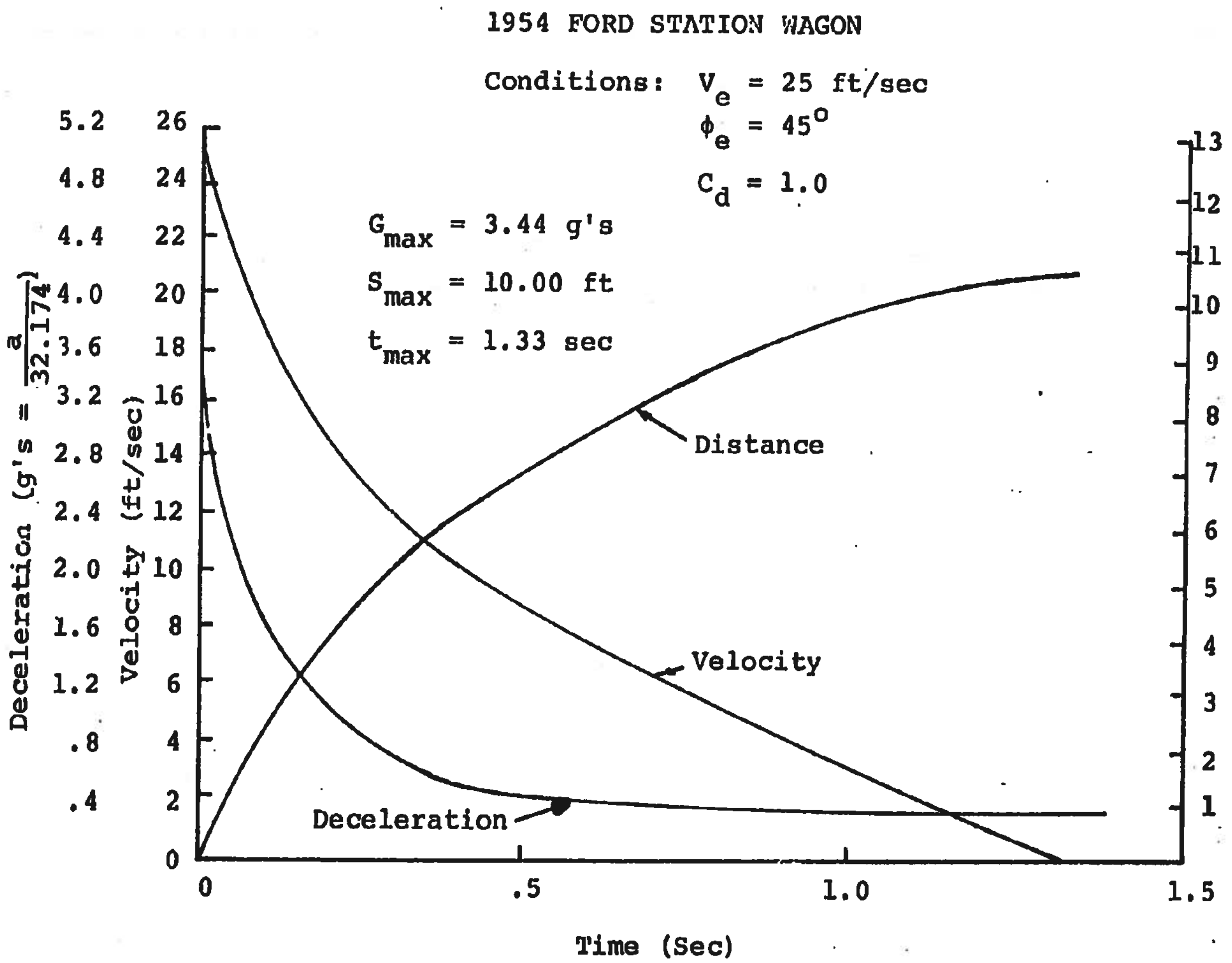


Figure 3.22. Deceleration, velocity and penetration distance for a 1954 Ford station wagon upon entry into a body of water for the condition shown. (Computerized Predictive Model--Program "B")

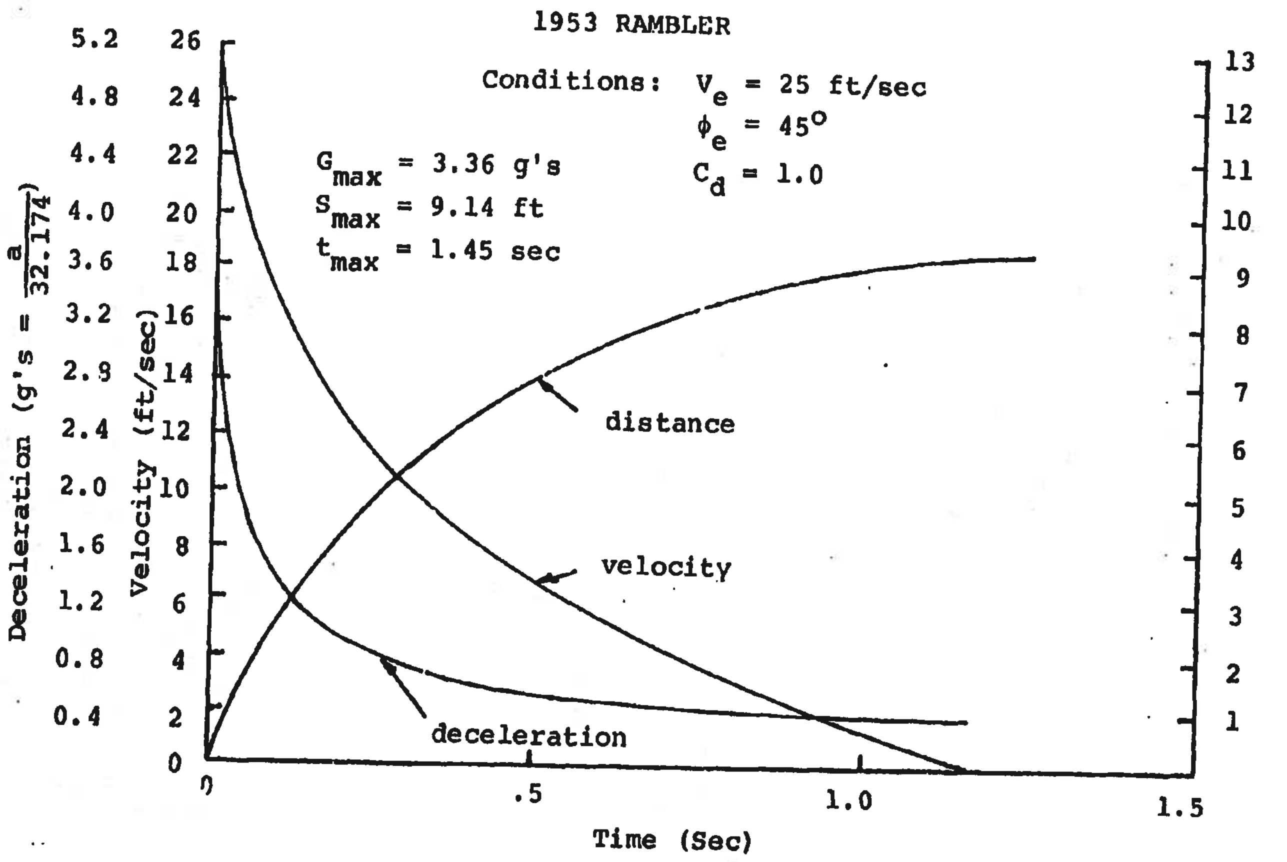


Figure 3.23. Deceleration, velocity and penetration distance for a 1953 Rambler upon entry into a body of water for the initial conditions shown. (Computerized Predictive Model--Program "B")

in the actual case and would occur only if the vehicle has an extremely blunt leading edge where the surface involving the total frontal area, A_c, enters the water completely, at t = 0 (i.e., vertical entry). This effect will be discussed more fully in the next section where the more sophisticated water-entry program is presented.

3.2.2.2 Literature survey of water-entry processes: A pertinent review article appearing in The Journal of Hydronautics (2) entitled "Review of Water-Entry Theory and Data" by Albert May, a consultant for the U.S. Naval Ordinance Laboratory, White Oak, Silver Spring, Maryland, was obtained early in the study. In it the state of the science concerning the understanding of the water-entry process is described as applied to air-launched missiles used primarily in anti-submarine warfare.

While the shape and velocity of these missiles are much different from those of passenger vehicles entering the water travelling at roadway velocities, the process of water-entry is similar. Thus, it appears that it would be possible to bring much information, both theoretical and experimental, to bear on the passenger car water-entry process.

The first part of May's review concerning the water impact forces is of such pertinence that the whole presentation of this section of his report will be quoted exactly as follows:

> In the past both the prediction and measurement of the forces at water impact have proved most difficult. The major theoretical obstacle is the unknown change in the shape of the boundaries, a shape which must be determined as part of the solution. Many attacks have been made on the problem, but practical results have come almost entirely from approximations based on a method proposed over 40 years ago by von Karman (3).
>
> Briefly, von Karman assumed that momentum is conserved during the impact phase of water entry. The momentum of the water is that of the added mass, which

is viewed as traveling with the missile at its instantaneous speed. The impact force arises from the acceleration of this water mass that was originally at rest. The method is at best a rough approximation, especially since the prediction of the added mass depends on the changing boundary, including the splash. Of the many predictions that have been based on the method, few appear realistic and these have been "corrected" by semiempirical approaches. The outstanding examples of the effective use of such "corrections" is the analysis of Shiffman and Spencer for the vertical entry of spheres (4).

Measurement of impact forces also has proved intractable because of the shock that the instruments must withstand and the rapid response required of them. Instrumentation is now catching up, and experimental measurements of deceleration are under way.

The measurement itself of the impact forces is not the whole problem by any means. Data have been published for the entry of missiles with a variety of nose shapes, of various sizes and weights, entering at various speeds; but the effects of mass, weight, buoyancy, and skin-friction drag have generally been completely disregarded. The result is that experimental data cannot be applied to a missile unless it is identical to that used in the experiment. Even if a missile differs only in weight, it is not evident how the experimental data can be applied. Shiffman and Spencer (4) laid an excellent foundation for a method of analysis. They assumed that for the water entry of a particular missile at a particular entry angle, the added mass is a function only of the distance the missile has penetrated the water. Of course, it is also proportional to the density of the water, ρ, and the cube of the missile radius, r. The added mass is not a function, however, of the mass of the missile or of its speed.

This concept assumes that the water flow is related by simple geometry to the motion of the missile, and that the added mass has always the instantaneous speed of the missile. Although it is quite difficult to predict theoretically the value of this added mass, a method may be built on the premise that it has an effective value at each penetration distance, a value that can be determined experimentally from measurements of deceleration.

Complete details of the method cannot be given here, but the process is substantially the following, for an analysis based on measurements of deceleration as a function of depth. Assuming first that all forces other than the hydrodynamic forces on the nose can be neglected, the added mass, M, can be written in the dimensionless form $M' = (2/\pi\rho r^3)M$. Figure 3.24 is a plot, from (4) of M' against b, the penetration distance in radii. It is for the vertical entry of spheres. It is easily shown that

$$dM'/db = C_{\rho_\infty}$$

the instantaneous drag coefficient related to the impact speed, for a body of infinite mass. Figure 3.25, which is taken from the same source (4), is a plot of impact drag coefficient against b, for various specific gravities of an entering sphere. The method that was derived for the prediction of the forces on a sphere can be used for the correlation of experimental data from entries of spheres of various sizes and densities, and the extension of the method to other nose shapes and to oblique angles of entry is straight-forward.

In analyzing data from the measurement of deceleration when nonhydrodynamic forces are acting, the hydrodynamic force is easily obtained by subtracting the effects of weight and buoyancy. When skin friction is significant, as in the case of the slender cone, it can be calculated also. Thus, we can compute the hydrodynamic force at any instant, but the determination of the added mass is more involved. The simple momentum equation cannot be used, because weight, buoyancy, and skin friction prevent momentum from being conserved, and skin-friction drag even contributes to the added mass. Still another complication is the following. In the plots of Figure 3.25, the graphs approach zero at large b, where the added mass is no longer changing. The actual force does not go to zero, however, but to a value determined by the steady cavity-running drag. Just how cavity-running drag builds up from zero at first contact, to the final value, is not known.

There are many problems here for which the solutions are not yet clear; but they are being worked on, and answers should be forthcoming.

The review article also contains sections on the effect of whip at entry, the water-entry cavity and the trajectory after water-entry. Since these sections do not contain any information pertinent to the analysis of Shiffman and Spencer on the vertical entry of spheres, they will not be discussed.

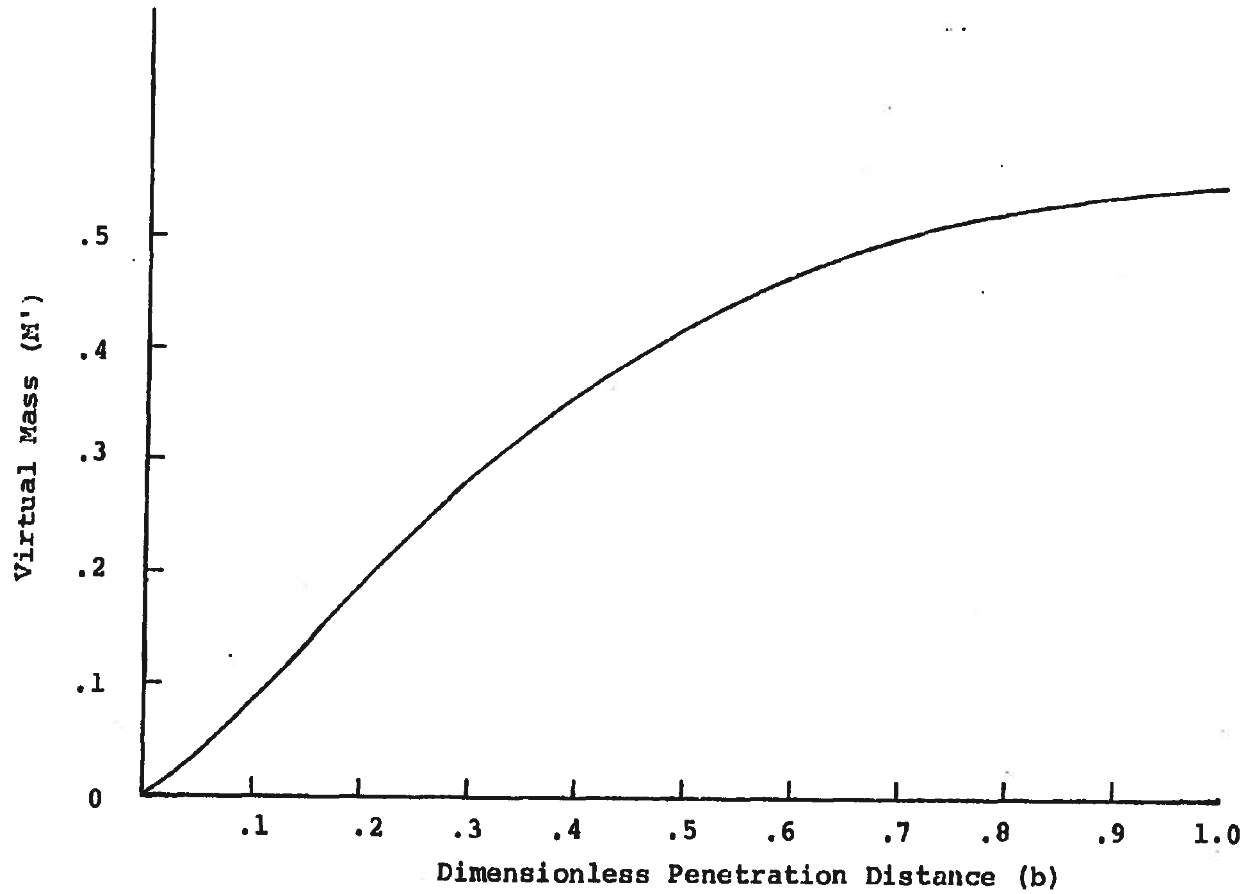


Figure 3.24. Virtual mass versus dimensionless penetration distance for spheres (after Shiffman and Spencer).

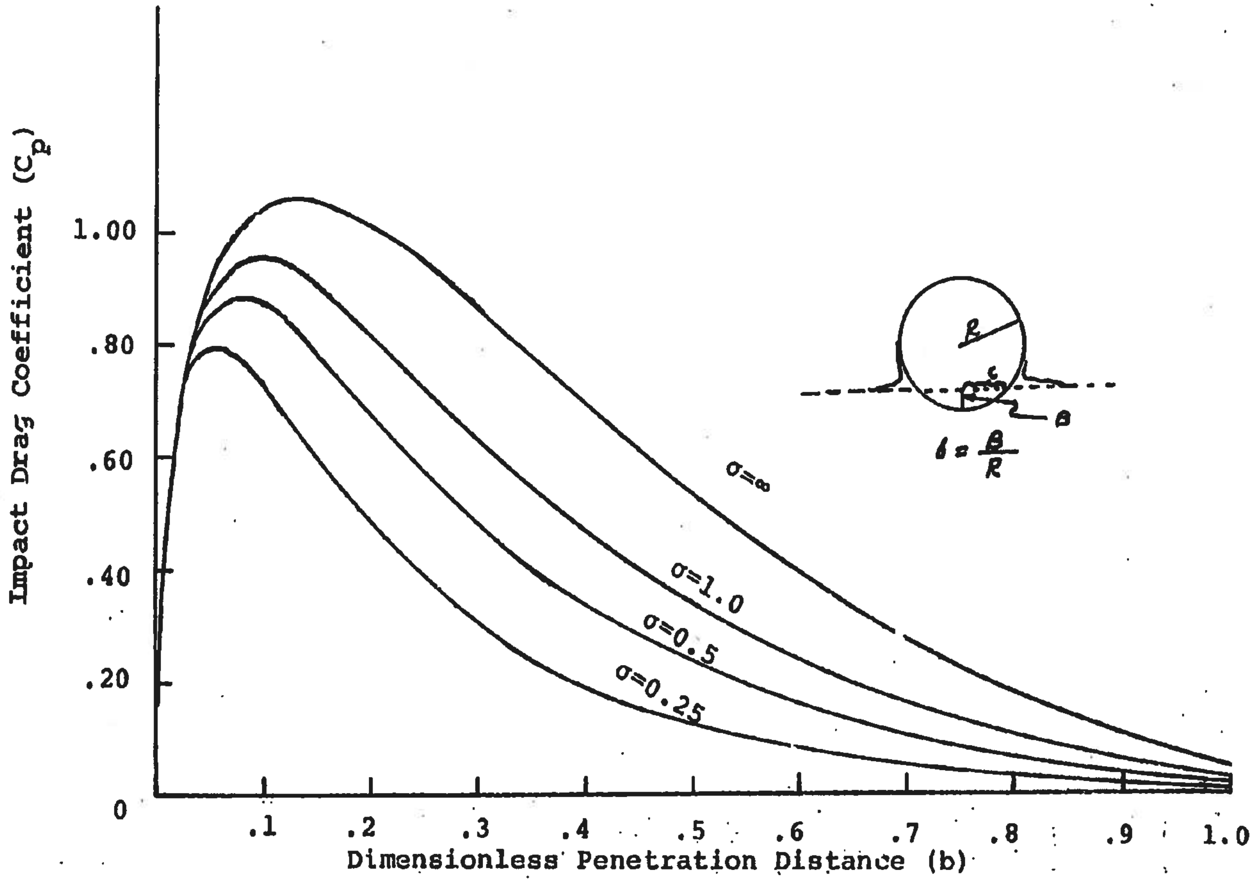


Figure 3.25. Impact drag coefficient versus dimensionless penetration distance for spheres (after Shiffman and Spencer).

However, the method proposed by the famous hydrodynamicist, T. von Karman (3) in his analysis of the impact forces on seaplane floats and extended to the use of spheres by Shiffman and Spencer (4) will be developed in the following section.

3.2.2.3 Development of the vehicle water-entry program "A" based upon the method of Shiffman and Spencer employing the "virtual mass" concept: The following analysis is essentially a summary of the analysis of Shiffman and Spencer (4) for the determination of the virtual mass, M, and the impact drag coefficient, C_p, which are both functions of time for the case of the vertical entry of spheres.

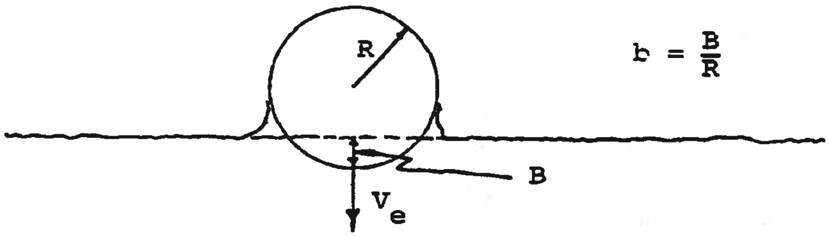
> The entry of a solid body from air into water may take place in two ways: (i) if the speed is small and if the surface of the body is smooth, the entry occurs without the formation of a cavity (smooth entry); (ii) if the speed is great or if the surface of the body is rough or has an irregular shape, the flow detaches from the body when it has penetrated a short distance below the initial surface level (rough entry). In either case there is an initial period following contact with the surface during which the body experiences the greatest deceleration and which is of such short duration that cavitation has not yet developed. The determination of the forces acting during this impact stage of the entry is important in the case of projectile shot or dropped into water, not only because of possible damage to the mechanism and nose but also because the impulsive forces and torques created by the impact influence the underwater trajectory of the projectile.

It is assumed that the nose of the projectile is spherical in shape and that the initial impact with the surface is vertical. The mass of the projectile is visualized as concentrated into a sphere of the same radius as the nose.

The resultant upward force, P, acting on the sphere in the impact stage can be expressed in terms of a dimensionless impact-drag coefficient, C_p. Let R be the radius of the sphere, and V_e be the initial entry velocity upon impact, and ρ the density of water. The impact force may be conveniently expressed as:

$$P = C_p \frac{\rho V_e^{2}}{2} \pi R^2 \qquad (3\text{-}1)$$

where C_p = impact drag coefficient.
The coefficient, C_p, depends upon time; it is zero when the sphere first strikes the surface, rapidly increases to a maximum value, and then decreases. The following sketch denotes this initial water-entry process.



The impact drag coefficient, C_p, can be expressed in terms of the "virtual mass," M, of the fluid. Let V be the downward velocity of the sphere at any instant of time, t, and let P be the resultant upward impact force exerted on the sphere. Then the sphere exerts a downward force, P, in the fluid and imparts momentum to the fluid. The virtual mass, M, of the fluid at a given instant, t, is given by:

$$P = \frac{d}{dt}(MV) \quad \text{or} \quad MV = \int_0^t P dt \qquad (3\text{-}2)$$

Let M_o be the mass of the incoming projectile. Neglecting gravity forces compared to the impact force, P, we have:

$$-P = \frac{d}{dt} (M_o V) \qquad (3\text{-}3)$$

Add Equations 3-2 and 3-3 and we obtain:

$$\frac{d}{dt} (M + M_o)V = 0 \qquad (3\text{-}4)$$

Integrating Equation 3-4 we obtain:

$$(M + M_o)V = M_o V_e \quad \text{or } V = \frac{V_e}{1+M/M_o} \qquad (3\text{-}5)$$

where V_e = entry velocity of the incoming sphere at the instant of contact with the fluid.

Let B = B(t) be the distance at time t, of the lowest point on the sphere from the initial fluid surface level. Then, the velocity, V, of the sphere is:

$$V = \frac{dB}{dt} \qquad (3\text{-}6)$$

Now differentiating Equation 3-5 with respect to t and using 3-3 it follows that:

$$P = \left[\frac{dM/dB}{1+M/M_o}\right] V^2 = \left[\frac{dM/dB}{(1+M/M_o)^3}\right] V_e^{\,2} \qquad (3\text{-}7)$$

If R denotes the radius of the incoming sphere we can introduce the two dimensionless quantities M' and b as:

$$M' = \frac{M}{\frac{1}{2}\pi\rho R^3},\ b = \frac{B}{R} \qquad (3\text{-}8)$$

We can then write, making use of Equations 3-1 and 3-7:

$$C_p = \frac{dM'/db}{(1+M/M_o)^3} \qquad (3\text{-}9)$$

For incoming projectiles of large mass compared to the mass of the water displaced by the hemispherical nose, M/M_o may be neglected compared to unity. Then the impact drag coefficient, C_p, is simply dM'/db. Also from Equation 3-5 the change in velocity, V, in the impact stage is small.

If M_o is not large compared to M, then the denominator in Equation 3-9 must be retained. It is convenient to recast the denominator in somewhat different form. Let σ be the specific gravity of the incoming projectile considered as though the whole mass were concentrated into a sphere (if the incoming projectile is not already a sphere). Then:

$$\sigma = \frac{M_o}{\frac{4}{3}\pi R^3} \qquad (3\text{-}10)$$

Using Equations 3-8 and 3-9 we can write the final expression for C_p:

$$C_p = \frac{dM'/db}{(1+\frac{3}{8\sigma}M')^3} \qquad (3\text{-}11)$$

The determination of the impact drag coefficient, then, reduces to obtaining an expression for the dimensionless virtual mass, M'.

In an earlier report, Shiffman and Spencer (5) obtained an expression for the virtual mass based upon the assumption that the surface of the water does not rise. In their subsequent analysis (4) a second approximation is included which contains corrections of two types. On the one hand, the surface of the water rises and wets a greater portion of the spherical surface than it would if the surface did not rise. The fluid therefore exerts pressure over a larger area and increases the total impact force. This is called the "wetting correction." On the other hand, the free surface rises and relaxes to a certain extent the restraint imposed on the sphere. This behavior is called the "surface correction."

The detailed analyses made by Shiffman and Spencer for these two corrections will not be reproduced here. Only the final expression for M'

$$M' = M'_L\ (b_1) - \int_o^b K_s db \qquad (3\text{-}12)$$

will be shown where M'_L = virtual mass of a lens-shaped body (approximated by an oblate spheroid)

b_1 = dimensionless penetration distance of a body of this shape

K_s = complex function of b for a body of this shape.

The expression for M' versus b is shown in Figure 3.24 and using the slopes of this curve, dM'/db, the expression for C_p, the impact drag coefficient, can be obtained. This result is plotted in Figure 3.25 for the specific gravity values σ = 0.25, 0.50, 1.0, and ∞. The curves show that the impact drag coefficient rises very rapidly to peak values of about unity, the maxima occurring when the sphere has penetrated to a distance of from 0.1 to 0.2 of a radius below the initial surface level. The value of C_p then decreases gradually until at about 0.7 radius (for $\sigma = \infty$), its value is equal to the experimentally determined "cavity"-drag value of about 0.3. For smaller values of σ the maxima are lower and shifted to the left.

The question arises whether in rough entry the cavity formation which takes place will interfere with the predicted results. It is known from both experiment and theory that the cavity begins to form in the case of a sphere, only after the sphere has penetrated to a distance somewhere between one-quarter of a radius and one radius. Thus, it would seem that the behavior of C_p as described in Figure 3.25 would apply, i.e., the rapid rise of C_p to the order of unity and the slower decline to the cavity drag value of 0.3. The brief impact stage in rough entry is the same as in smooth entry.

The vehicle water-entry program (Program A) follows directly from the analysis of Shiffman and Spencer described in the preceding paragraphs.

The entry force, P, is taken from Equation 3-1:

$$P = C_p \frac{\rho V_e^2}{2g} \pi R^2 \tag{3-1}$$

where C_p = impact drag coefficient for the case of the vertical entry of a spherical body as a function of time as shown in Figure 3.25

ρ = specific weight of water

By Newton's law this force can be expressed as a product of the mass of the body entering the water $M_o = \frac{W}{g}$ and the acceleration as:

$$P = -C_p \frac{\rho}{2g} V_e^2 A_{eff} = \frac{W}{g}\frac{dV}{dt} \qquad (3\text{-}13)$$

where A_{eff} = effective area of the body entering the water based upon an equivalent sphere where:

$$A_{eff} = \pi R_{eff}^2$$

and b as described on page 3-103 is defined as $\frac{s}{R_{eff}}$ with s the actual penetration distance below the surface.

Let us for convenience define A_{eff} for non-spherical bodies as the total body volume, V_t, divided by the characteristic length of the body along its path of motion, ℓ_s, i.e.:

$$\frac{V_t}{\ell_s} \equiv A_{eff}$$

A_{eff}, then, will represent an effective frontal area of a body such as a vehicle entering the surface of the water.

Water-entry Program A, documented in Appendix C-1 was developed by means of the solution to Equation 3-13 using the fourth-order Runge-Kutta numerical integration scheme employed previously in water-entry Program B. For simplicity, input tables were used for values of C_p versus b for the specific gravity of the vehicle of interest.

3.2.2.4 Comparison of the results of the water-entry program "B" and the initial water-entry program "A": For a comparison with the cases previously shown for Program B, the constants involving the characteristics of the 1961 2-door Ford were employed for the vertical entry case (ϕ_e = 90°) for two entry velocities, V_e = 25, and 88 ft/sec. The constants for the case of the vehicle are:

$W = 3675$ lb

$\ell_s = 17.49$ ft

$V_t = 316$ ft^3

$A_{eff} = \frac{V_t}{\ell_s} = 18.066$

$K_D = 5.251$ (for cavity drag $C_D = 0.3$)

$K_B = 420.95$ (for flotation volume $V_s = 118$ ft^3)

Two cases were employed for each velocity of entry. The first case was run using as a basis for comparison water-entry Program B (from the quasi-steady analysis) employing as a drag coefficient the cavity-drag coefficient value of 0.3 suggested by Shiffman and Spencer.

The second case was run using water-entry Program A to describe the initial entry process and after the impact coefficient had decreased from its maximum value to 0.3 (the cavity-drag value), the resulting values of vehicle velocity and time were used as inputs to water-entry Program B which was used (with a constant C_D value of 0.3) to describe the remainder of the entry process.

3.2.2.5 Comparison of the results using the quasi-steady water-entry program "B" and the unsteady flow water-entry program "A": The results of this computer study are shown in Figures 3.26 through 3.31 for the vehicle displacement, velocity, and deceleration force as functions of time. In Figures 3.26 and 3.27 the displacement (penetration distance) of the leading edge of the vehicle is plotted for the case of the 1961 2-door Ford versus elapsed time after entry for the two-entry velocities, 25 ft/sec and 88 ft/sec, respectively. The dashed curves are for the

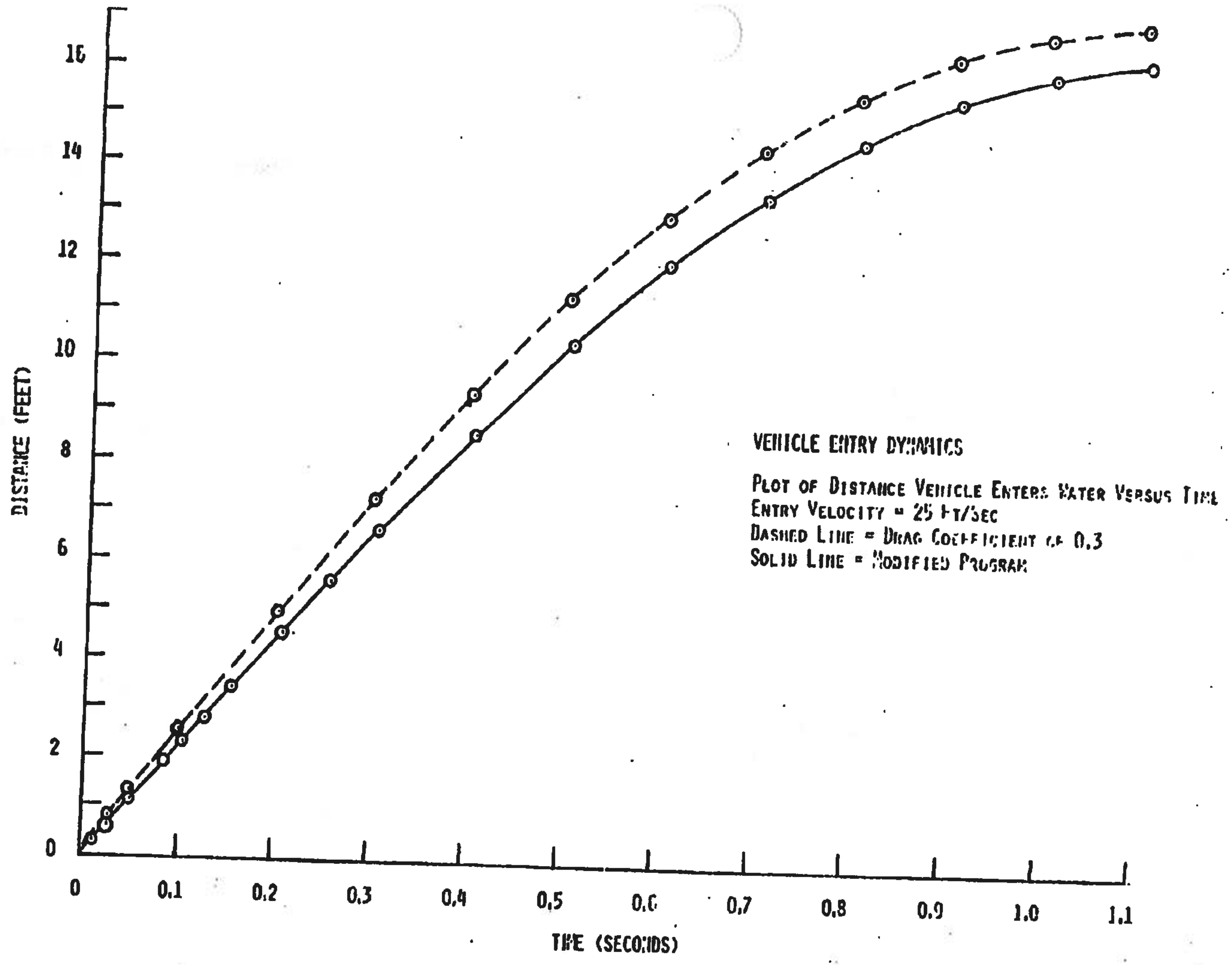


Figure 3.26. Vehicle vertical water-entry dynamics, displacement versus time, comparing two computer programs (1961, 2-door Ford, V_e = 25 ft/sec).

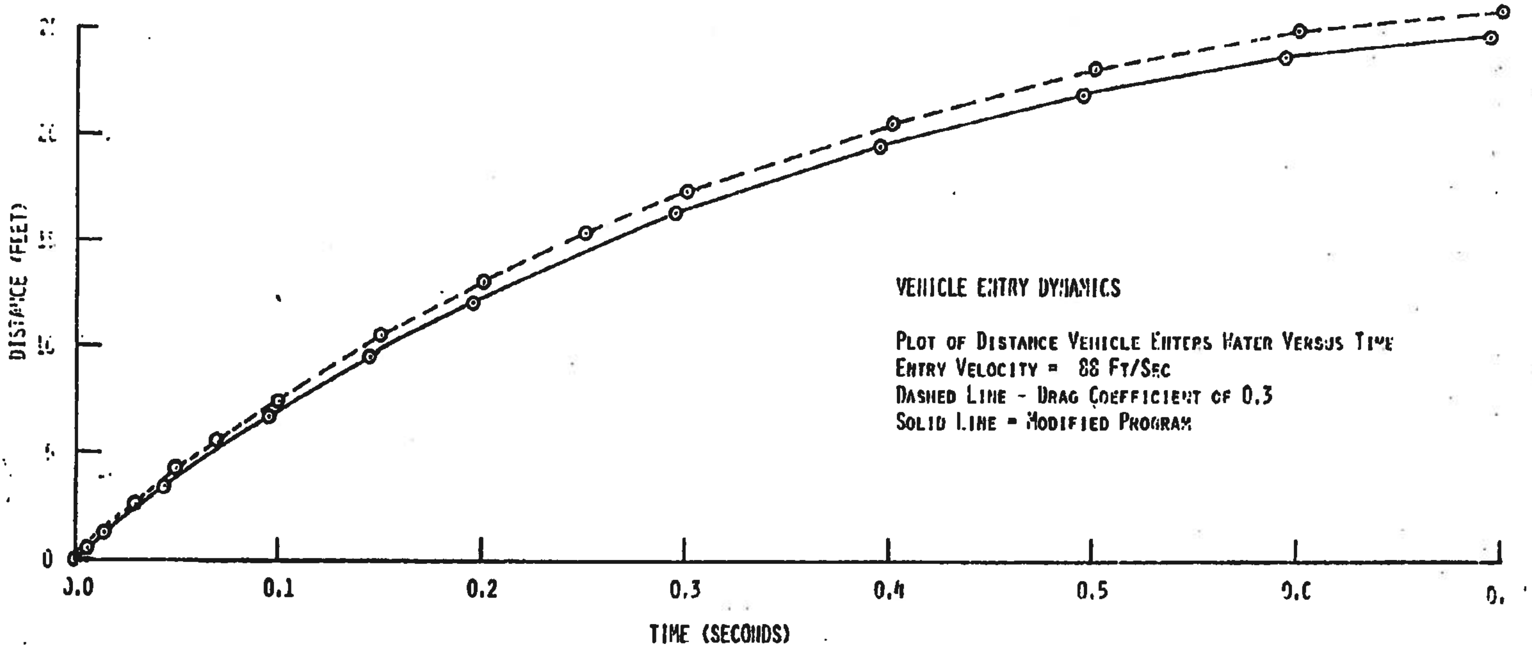


Figure 3.27. Vehicle vertical water-entry dynamics, displacement versus time, comparing two computer programs (1961, 2-door Ford, V_e = 88 ft/sec).

quasi-steady flow, water-entry Program B using a drag coefficient of 0.3 throughout. The solid curves referred to as the combined program show the results using the unsteady flow, water-entry Program A to describe the initial entry process until the impact drag coefficient decays to the cavity drag value of 0.3. At this point, the displacement values are 1.29 ft (for both entry velocities); the vehicle velocities are 21.55 ft/sec and 75.88 ft/sec and the elapsed times are 0.056 sec and 0.016 (for the entry velocities 25 ft/sec and 88 ft/sec respectively). Using these values as inputs to water-entry Program B, the remainder of the entry process is shown by the rest of the solid curves using the constant cavity drag coefficient of 0.3. It can be seen that the curves are quite close throughout with slightly lower values of displacement predicted by the use of the combined water-entry programs (Program A plus Program B) for each entry velocity case. It will be noted that the maximum penetration distance predicted using the different water-entry programs is approximately 16 ft (nearly full vehicle submergence of 17.49 ft) for the lower entry velocity and about 25 ft (about 1½ vehicle lengths) for the higher entry velocity.

Figures 3.28 and 3.29 show the vehicle velocity versus time predicted using the different water-entry programs down to nearly zero velocities.

For V_e = 88 ft/sec, the time when the vehicle velocity is actually reduced to zero is about 0.8 sec and is not shown on the figure. Again, as in the case for the vehicle displacements, the velocities predicted using both water-entry programs are quite close except in the very short times after initial entry.

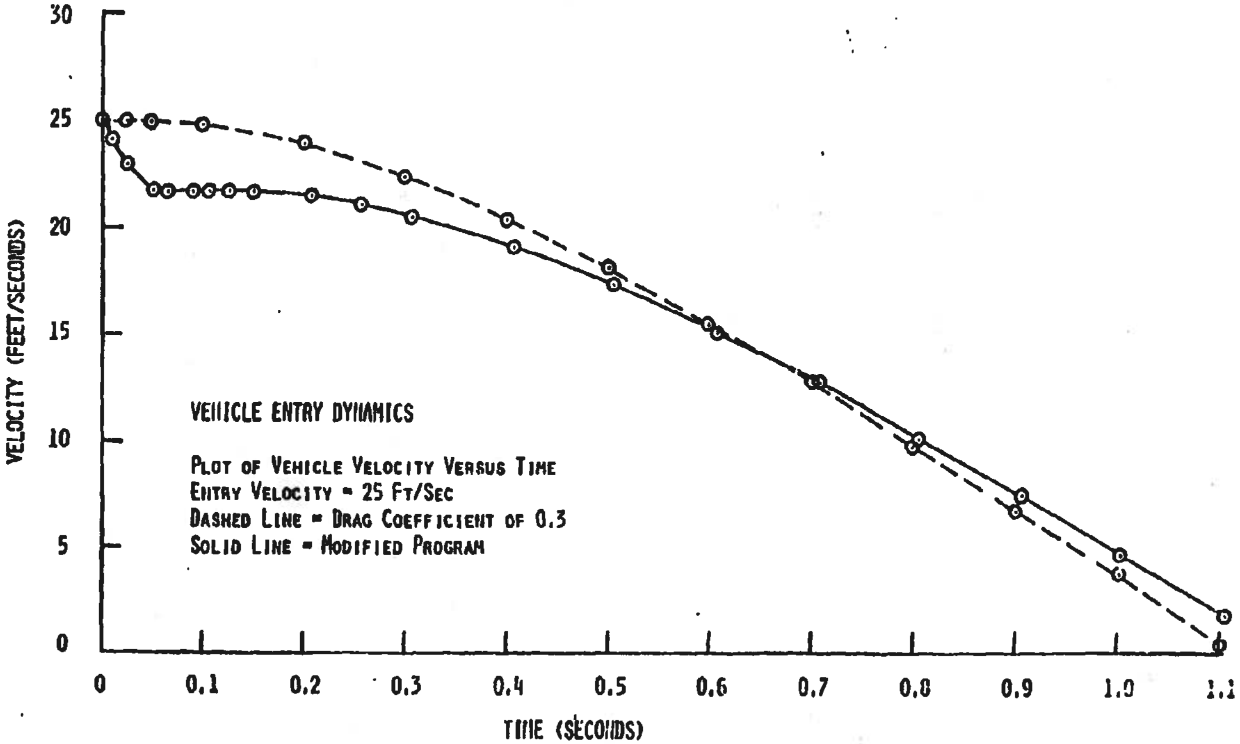


Figure 3.28. Vehicle vertical water-entry dynamics, velocity versus time, comparing two computer programs (1961, 2-door Ford, V_e = 25 ft/sec).

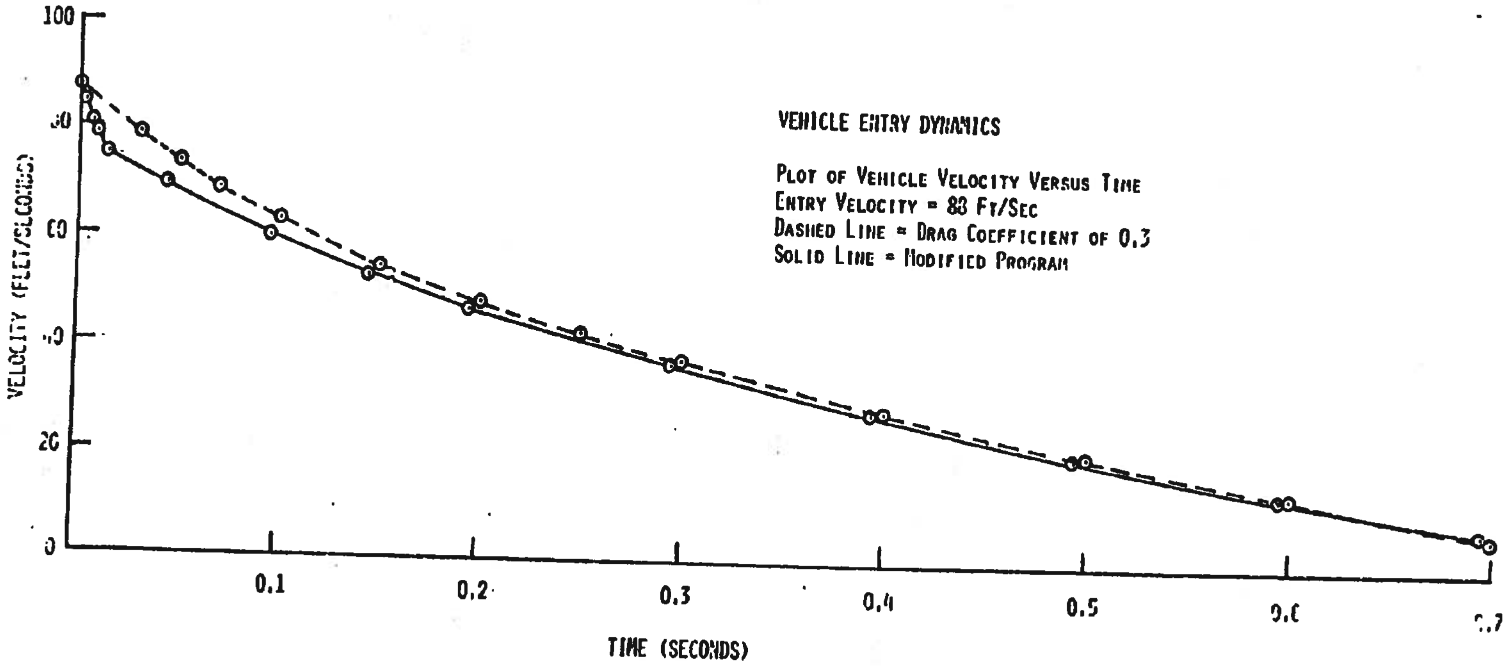


Figure 3.29. Vehicle vertical water-entry dynamics, velocity versus time, comparing two computer programs (1961, 2-door Ford, V_e = 88 ft/sec).

Figures 3.30 and 3.31 show the deceleration force measured in g's versus time predicted using the different water-entry programs.

For the lower entry velocity, V_e = 25 ft/sec, the dashed curve in Figure 3.30 showing the forces predicted using the quasi-steady water-entry Program B begins at slightly negative values (acceleration forces) and increases past zero becoming deceleration forces for the rest of the entry process. The solid curve describing the combined programs exhibits a rapid rise from zero to nearly three g's and then a rapid decay to somewhat lower deceleration forces (than the dashed curve) for the rest of the entry process. The reason for the regions of acceleration forces for both water-entry programs for this low entry-velocity is perhaps not obvious. At these low entry velocities the low force components due to hydrodynamic drag and buoyancy (deceleration forces) do not exceed the inertial forces due to gravity (an acceleration force) until the vehicle has penetrated to a distance which is sufficient for the buoyancy force to increase to high enough values to overcome the inertia forces so that the vehicle actually begins to decelerate.

Figure 3.31 shows the case for the higher entry velocity (88 ft/sec). Here hydrodynamic drag forces predominate over inertial forces for both curves (no regions of acceleration forces exist). The dashed curve, showing the forces predicted by water-entry Program B, begins at a value of about ten g's and decreases monotonically to some low minimum value (about two g's) at the termination of the entry process. The solid curve showing the forces predicted by the combined programs exhibits a rapid rise from zero to about 35 g's at very short times after entry, then a rapid decay to values of the same order as the other curve for the rest of the entry process.

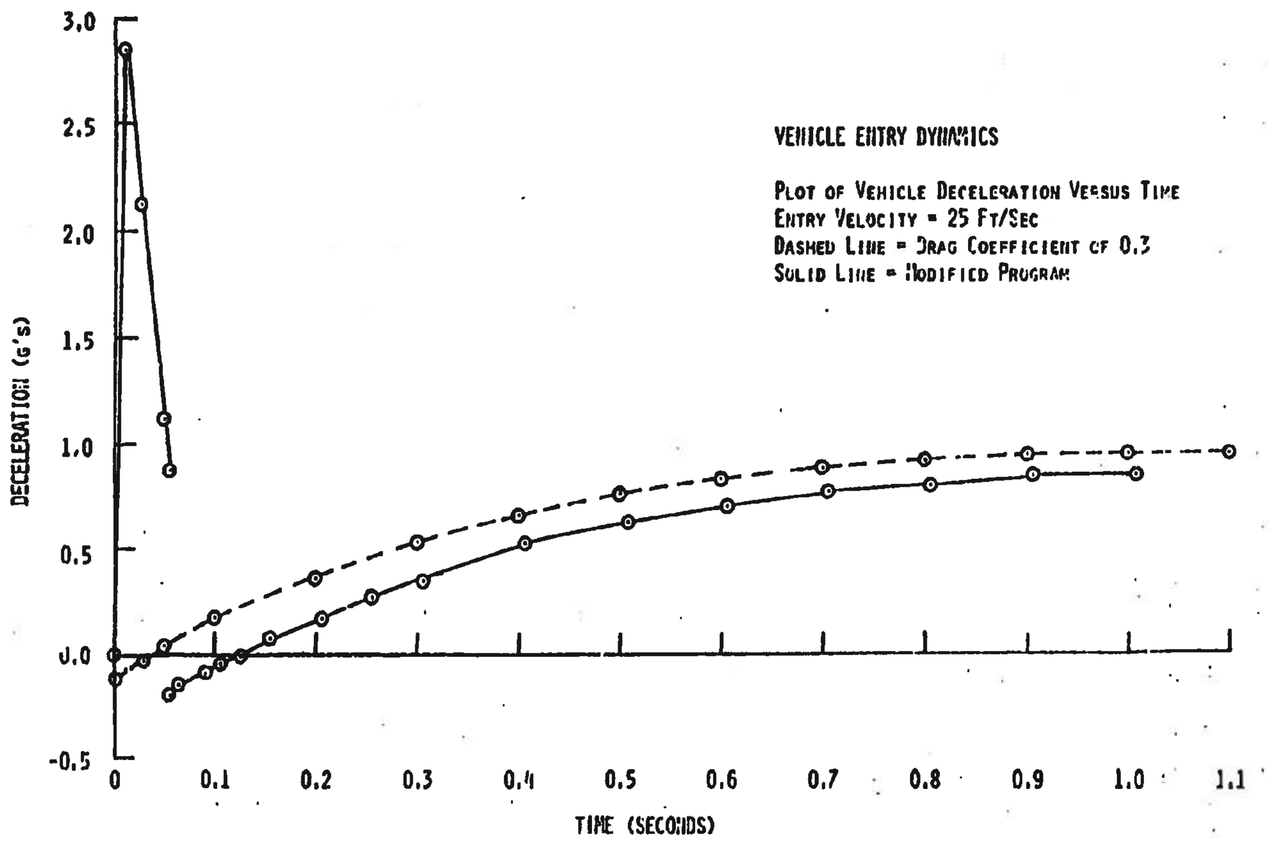


Figure 3.30. Vehicle vertical water-entry dynamics, deceleration versus time, comparing two computer programs (1961, 2-door Ford, V_e = 25 ft/sec).

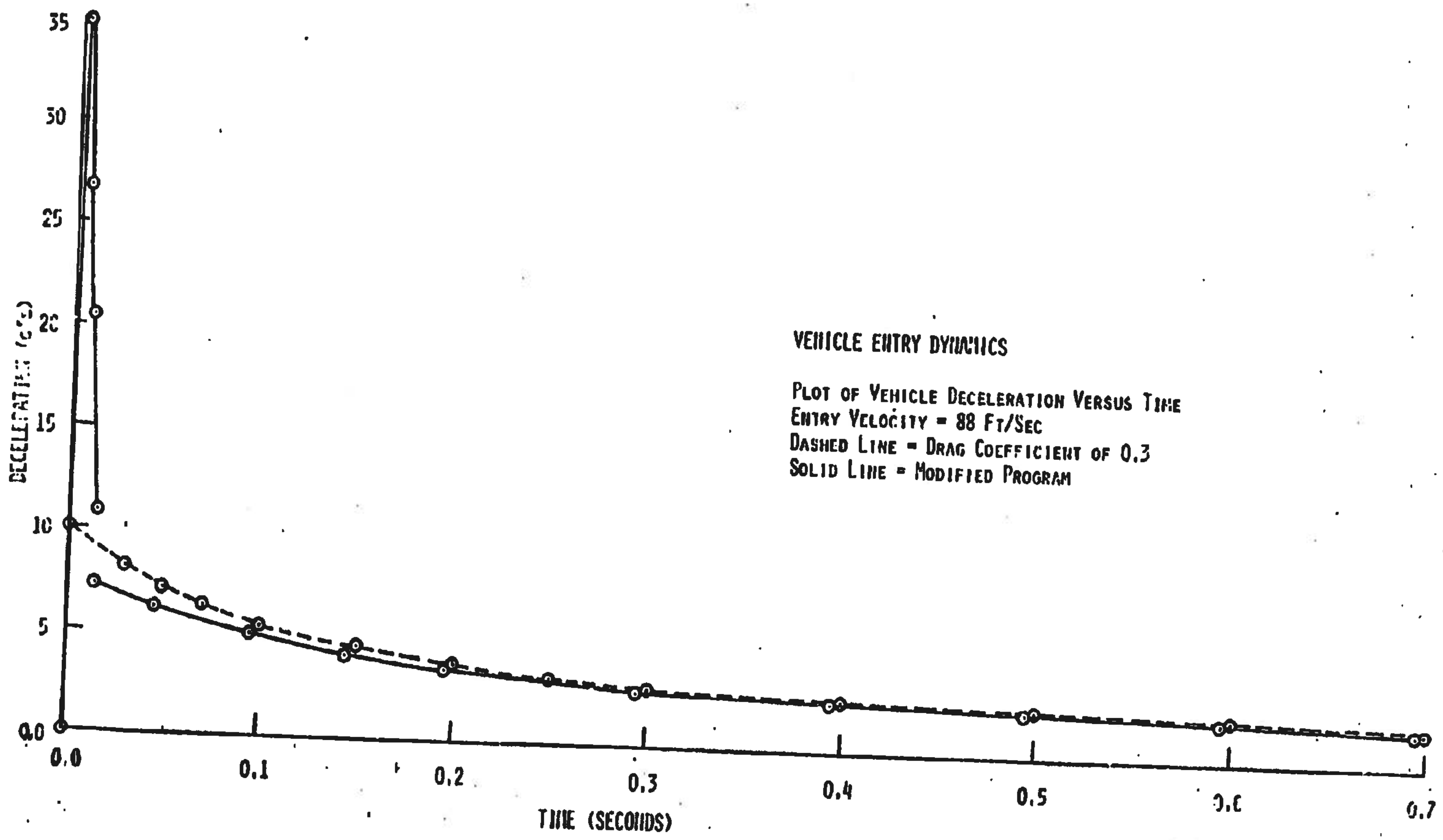


Figure 3.31. Vehicle vertical water-entry dynamics, deceleration versus time, comparing two computer programs (1961, 2-door Ford, V_e = 88 ft/sec).

In general, it can be concluded that the results of the vehicle dynamics using both water-entry programs are quite similar except for marked differences in the initial phases of the entry process where the "virtual mass" effects using Program A predominate. However, it appears that the period of time where these effects occur is of such short duration that the cumulative result on the predicted maximum penetration distances is quite small. Of greater significance, perhaps, is the much larger penetration distance predicted by both programs using the cavity-drag coefficient of 0.3 suggested by Shiffman and Spencer. If the vehicle dynamics associated with this cavity-drag coefficient more closely describe an actual vehicle entry process than the assumed bluff-body drag coefficient of 1.0 used in the earlier parametric studies (described in Figures 3.20 through 3.23), the following significant conclusion can be drawn:

At the higher entry velocities, larger penetration distances than the vehicle length are predicted. Thus, if one or more of the vehicles' windows are open during the entry process (or if doors come open upon impact) sufficient time is present for the vehicle to fill with water during its first underwater penetration so that it never rises to the surface.* Fven if the vehicle does not sink after the first water-entry penetration, it is possible that the overall sinking times are reduced to such an extent that vehicular escape while the vehicle is still floating becomes virtually impossible.

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*During the 1961 Michigan submergence tests it was noted, at the very low entry velocities employed, that only moderate amounts of water entered the windows in those tests where one or more windows were left open prior to submergence. Even for those cases, however, measurable decreases in the overall vehicle sinking times were recorded.

3.2.3 Dry-Land Vehicle Leak-Rate Simulation and Correlation Studies

A correlation has been made of the actual water-leak rates derived from the submergence experiments of March 1970 (1) involving the 1967 Chevrolet Impala, 4-door hardtop sedan and "dry-land" air leak-rate tests performed on the same vehicle. The following paragraphs give the background and motivation for this type of study and Appendix C-1 gives the supporting analysis.

It became increasingly apparent that because of the costly and time consuming nature of full-scale vehicle submergence experiments to determine sinking characteristics of automotive vehicles that a much simpler method, preferably one in which the vehicle was not damaged, would be highly desirable.

It was concluded that it would be possible to simulate experimentally an important vehicle property, i.e., the vehicle water-tight integrity, without performing an actual water submergence test of a particular vehicle. It is noted that a quantitative measure of a vehicle's water-tight integrity would be the water leak-rates and locations and the actual vehicle sinking times.

The proposed method was an experimental procedure termed a "dry-land" air leak-rate test. It involved the application of a pressure differential between the ambient atmospheric pressure and the pressure (vacuum) created in the connected passenger and trunk compartments of a typical passenger automotive vehicle. The apparatus envisioned was most conveniently a high volume flow-rate blower used as a vacuum pump, the intake of which is connected to a suitable opening in the vehicle. The action of the blower reduces the pressure level in the passenger and trunk compartments of the vehicle causing air to leak into the vehicle from the surrounding atmosphere through numerous openings (small and large) in the vehicle structure. The direction of the pressure-differential (an over-pressure) is the same as that existing on the openings during an actual vehicle submergence process (for those openings that were positioned below the external vehicle waterline). The exhaust volume flow-rate is measured by the most convenient scheme to determine the total air volume flow-rate of all the vehicular openings (leaks) for a comparison with the measured water leaks during an actual water submergence test. It is noted that this type of submergence test had been performed several times using the 1967 Chevrolet during previous studies (1) wherein vehicle sinking times and water level positions had been recorded. It remained to be determined if a correlation could be obtained between the results of these tests and the proposed simulated dry-land leak-rate tests. The following sections present the results of these tests performed on the 1967 Chevrolet Impala and three other passenger vehicles. Appendix C-2 gives supporting theoretical analyses of the proposed water leak-rate and air-leak rate mechanisms, and relations which can predict the water-leak flow rates on the basis of measured air-leak tests.

3.2.3.1 Air leak-rate experiments involving the low capacity (350 CFM) blower: The experimental equipment for the introductory experiments on the 1967 Chevrolet Impala utilized a centrifugal air-blower rated at about 3 inches-H_2O delivery pressure at a delivered volume flow-rate of 350 CFM. Characteristic of the behavior of this type of blower was somewhat higher volume flow-rate value at a zero pressure head delivery pressure and a somewhat lower value at a slightly higher delivery pressure.

A schematic view of the instrumentation used during these introductory dry-land air leak-rate experiments is shown on page C=28 of Appendix C.2. However, for accuracy, a 3 inch H_2O Meriam-type inclined manometer was used to determine the dynamic pressure, q, at the blower outlet and the simple U-tube manometer shown in the sketch was used to measure the pressure differential existing between the interior vehicle compartment pressure and atmospheric pressure. A velocity traverse was made of the 3-inch diameter exhaust pipe from the blower and the velocity discharge coefficient, $C_d=0.90$, was measured. The volume flow-rate could then be determined by simply measuring the dynamic pressure of air at the center-line of the discharge line, and then making use of Equation II-7 from Appendix C-2,

$$Q_{air} = \bar{V}_e A_e = C_d A_e \sqrt{\frac{2g}{\rho_{air}}} \sqrt{q_{air}} \qquad \text{(II-7)}$$

where Q_{air} is the volume air flow-rate.

The intake pipe of the blower was connected by a flexible pipe (containing a simple adjustable valve to regulate the flow) to a circular cut-out in a ¼-inch thick plywood panel replacing the top portion of the window in a partially rolled down position. This technique allowed for a large intake opening in the vehicle without damage or the introduction of any additional leaks. A photograph of a portion of the experimental set-up for subsequent experiments using the low-capacity blower is shown in Figure 3.32. Figure 3.33 shows the experimental set-up which was employed in the later experiments using the high capacity blowers. This figure shows the intake and discharge pipes as well as the U-tube and inclined manometers used for the pressure measurements previously mentioned.

The 1967 Chevrolet Impala was selected for the first series of tests. It was determined from preliminary experiments that the maximum pressure differential, ΔP, that could be maintained by the low-capacity blower was only about one inch of H_2O. It was concluded that this value was not nearly as large a pressure differential as that required to simulate the water-head of the leaks that occurred during vehicle submergence. However, the following

Figure 3.32. Dry-land vehicle leak-rate experimental test setup involving the low-capacity blower.

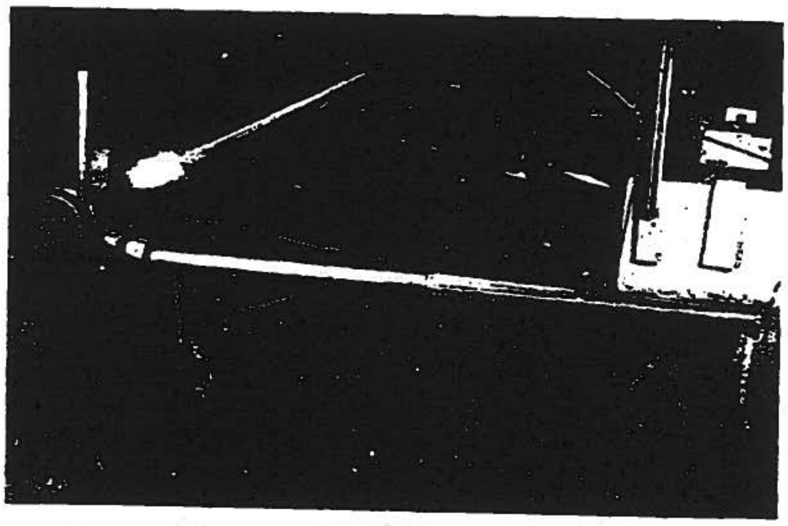

Figure 3.33. Dry-land vehicle leak-rate experimental test setup involving the high capacity blowers.

exploratory tests were performed primarily to establish the relative leak magnitudes and to approximate locations of the leaks in this vehicle at a low pressure differential.

First, the vehicle was taped (primarily on the outside of the vehicle) on all openings around doors, windows, trunk compartment lid, tail lights, fire-wall openings floor pan, air-intake grill and, in effect, all possible leak areas that could be taped. The blower was then turned on and the intake valve was adjusted so that a pressure differential of 0.60 in H_2O (arbitrarily selected) was recorded. The dynamic pressure q_{air} was also measured at the outlet of the blower discharge pipe for the determination of the volumetric air flow-rate, Q_{air}. Then in a series of progressive steps, the tape was removed from certain areas of the vehicle and the intake valve was adjusted for each new leak condition so that a constant value of ΔP (0.6 in H_2O) was maintained. The dynamic pressure q_{air} was recorded for each leak condition.

The results of these tests are summarized in Table 3.16. It can be seen that a reduction of nearly one-half in the over-all leak rate magnitude (Q_{air}) was effected by the taping scheme compared to the case of the vehicle in the original untaped condition. The initial condition leak rate (with the air intake grill open) was 320 CFM at a compartment pressure differential of 0.60 in H_2O with a residual leak rate of 163 CFM for the maximum taped condition. The most significant leak differential was obtained around the doors and windows (which can be expected from a hardtop body styling) and amounted to 107 CFM or 33.5 percent of the total.

A personal vehicle, a 1965 Pontiac Tempest 4-door Sedan, was selected for a follow-up experiment for comparison purposes. This vehicle was chosen for the following two reasons:

1. It was a used car of about the same vintage except that it was a 4-door sedan with an inherently superior

TABLE 3.16

DRY LAND LEAK-RATE SIMULATION EXPERIMENT EMPLOYING 1967 CHEVROLET IMPALA 4-DOOR HARDTOP*

CONDITIONS FOR EXPERIMENT: DIFFERENTIAL PRESSURE MAINTAINED INSIDE VEHICLE WITH VACUUM PUMP
DIFFERENTIAL PRESSURE = 0.60 IN. H_2O (VACUUM)

**Leak Location	Approximate Leak Flow Rate (CFM)	Differential CFM	% Total	Comments
Initial Condition	320	-	100	Kick vents closed Air intake open
1. Air Intake	308	12	3.75	Air intake closed
2. Front firewall & door trim mouldings	284	24	7.5	Taped around obvious leaks in firewall
3. Left side windows & doors	239	45	14.1	Taped both inside & outside of doors & windows
4. Right side windows & doors	177	62	19.4	Taped both inside & outside of doors & windows
5. Trunk	173	4	1.25	Taped inside & outside of trunk
6. Miscellaneous leaks in floor pan & firewall	163	10	3.12	Taped both inside and outside where possible

*Vehicle used during 1969-70 DOT Contract Submergence Experiments at FAA Center.

**All leaks sealed using duct tape.

TABLE 3.16--Concluded

Leak Location	Approximate Leak Flow Rate (CFM)	Differential CFM	% Total	Comments
7. Residual leaks	-	163	52.2	Remaining leaks primarily around firewall area

sealing system around the doors and windows.

2. It had a patented "Ziebart" undercoating process applied when new (cost $50 in September, 1965) which presumably reduced the multitude of small leaks throughout the vehicle structure.

Table 3.17 summarizes the results of these tests. For the tests of this vehicle, only the external gaps around the doors and windows were taped. The maximum air leak-rate measured for this vehicle was a Q_{air} of 221 CFM for the same initial conditions as the 1967 Chevrolet (all windows and doors closed with the intake grill open). The largest percentage leak reduction for the Tempest occurred when the intake grille was closed causing a leak reduction of 66 CFM or about 30 percent of the total. Taping around doors and windows effected a further leak reduction of 37 CFM or 17 percent of the total. The remaining residual leaks for the case of the Tempest was 118 CFM or about 54 percent of the total.

It can be seen that the Tempest tested exhibits its largest measured margin over the Chevrolet for Condition 1 with the vehicle's air-intake grill closed. For this case, the Tempest exhibited only about 50 percent of the leak-rates measured in the Chevrolet under similar conditions. As expected, the leak-rates around the doors and windows of the Tempest amounted to only 17 percent of the total while the leak rate around the doors and windows of the Chevrolet amounted to 33 percent of the total or nearly twice that of the Tempest. Also, for the Tempest in Condition 1 with the intake grill closed, the measured leak-rate of 155 CFM was somewhat less than the Chevrolet in Condition 7 with all areas taped. This result, as expected, indicates the inherent superiority of the 4-door sedan type sealing system, and over-all air-tightness due to the extensive undercoating process for the Tempest. In fact, it shows that the built-in air-tight integrity of the Tempest is even superior

TABLE 3.17

DRY LAND LEAK-RATE SIMULATION EXPERIMENT EMPLOYING 1965 PONTIAC TEMPEST CUSTOM 4-DOOR SEDAN*

CONDITIONS FOR EXPERIMENT: DIFFERENTIAL PRESSURE MAINTAINED INSIDE VEHICLE WITH VACUUM PUMP
DIFFERENTIAL PRESSURE = 0.6 IN. H_2O (VACUUM)
(SIMILAR TO TEST ON 1967 CHEVROLET IMPALA)

Leak Location	Approximate Leak Flow Rate (CFM)	Differential CFM	% Total	Comments
Initial Condition	221	-	100	Kick vents closed Air intake open
1. Air Intake	155	66	29.9	Air intake closed
2. Doors & windows	118	37	16.7	Taped around all four doors and windows
3. Residual Leaks	-	118	53.4	Numerous small leaks of undetermined origin

NOTE: Initial Condition
Leak Rate 69% of 1967 Chevrolet

Leak rate with intake vent closed 95% of residual leaks measured on 1967 Chevrolet

*Vehicle had patented "Ziebart" undercoating process applied when new (cost $50) to the taping technique used on the Chevrolet, for the condition where all possible leak areas were taped. That is, the residual leak rates of the Chevrolet were still slightly greater than those of the Tempest in its original condition with the air-intake grille vents closed.

Several other vehicles which were available were also tested using the low capacity blower. No taping was done with these vehicles. The conditions chosen for the tests were similar to the initial conditions chosen for the tests on the 1967 Chevrolet and the 1965 Tempest. Measurements were made with all windows closed and the cowl air-intake vents open at a differential pressure in the passenger and trunk compartment of 0.60 in H_2O (vacuum). The absolute measured leak-rates for all the vehicles tested in the order of increasing leak rate is as follows (including the 1967 Chevrolet and 1965 Tempest for comparison purposes):

	Vehicle	Leak Rate Q_{air} (CFM)
1.	1969 Volkswagen, Mod. 113, 2-door sedan	191.5
2.	1965 Pontiac Tempest, 4-door sedan	221.0
3.	1970 Ford Pinto, 2-door sedan	235.0
4.	1969 Ford Mustang, 2-door hardtop	320.0
5.	1967 Chevrolet Impala, 4-door hardtop	320.0
6.	1969 Oldsmobile Toronado, 2-door hardtop	321.0

Two groups of vehicles are evident in making a comparison on the basis of the measured leak rates. The lowest leak-rate group (with leak-rates in the order of 200 CFM) are all sedans with inherently superior door and window seals than the second group, all hardtop models, having almost identical measured leak rates of 320 CFM.

It is surprising that the more expensive, late-model Oldsmobile did not exhibit more air-tight characteristics than the other lower-priced hardtop models. Perhaps the air-intake vent system for the Oldsmobile (which was the only vehicle containing a factory installed air-conditioning system) was much more extensive than the other models which were not built for air-conditioning.

A second series of dry-land simulation tests was conducted using the 1967 Chevrolet Impala and the 1965 Pontiac Tempest. These tests were motivated by the conclusions reached in Appendix C-2 under the section, Air-Flow Measurement Analysis. On the basis of this analysis it was shown that the following relationship exists between the measured dynamic pressure (q_{air}) at the blower discharge and the pressure differential (ΔP_{air}) imposed on the vehicle passenger and trunk compartments.

$$q_{air} = \Delta P_{air}\left[\frac{A_{air}}{A_e C_d}\right]^2$$

Since q_{air} is proportional to the square of the discharge velocity (V_e^2) at the blower discharge location, it is also proportional to the square of the measured volume flow-rate $(Q_{air})^2_{measured}$, and it follows that:

$$(Q_{air})^2_{measured} = (A_{air})^2 \underset{\text{constant}}{\underbrace{\frac{2g}{\rho_{air}}}} \Delta P_{air} \qquad \text{(II-8)}$$

under the assumption that A_e does not change in an experiment and if the variation of the discharge coefficient is measured during an experiment.

It was concluded that if an experiment were performed to measure the pressure-differential leak-rate signature of a given vehicle that a linear relationship would exist between the measured dynamic pressure at the blower-discharge area and the pressure differential in the vehicle compartment for all possible values of ΔP_{air} and Q_{air} depending upon the air-tight integrity of the vehicle tested and the capacity of the blower used.

Figure 3.34 shows a comparison of the results of three ΔP-leak-rate signatures up to the maximum capacity of the low flow-rate blower used in these experiments. Two experiments were performed, one with the Tempest in Condition 1 of Table 3.17 and two for the Chevrolet, Conditions 1 and 7 of Table 3.16. These conditions are simply labeled taped and untaped in Figure 3.34. It can be seen that for both vehicles the ΔP_{air} versus q_{air} plots are concave upward, with the curve for the Tempest of considerably greater slope (starting from the origin) than the curve for the Chevrolet in a similar untaped condition. It is also of interest to note the close similarity of the curves of the two vehicles for the case where the Chevrolet has been completely taped.

A somewhat more important conclusion (presented in Appendix C-2) can be made regarding the non-linearity of the slopes of the curves representing two different model cars with different window and door sealing methods. On the basis of the theoretical analysis, any non-linearity of the ΔP_{air} versus q_{air} curves would most likely be due to a change in the air-leak areas, A_{air}, due to the force on the various air seals changing at different values of ΔP_{air}. This effect appears to be in evidence of all three curves indicating that the air-leak areas, A_{air}, actually decrease with ΔP_{air}, caused presumably by a compression of the air seals around doors and

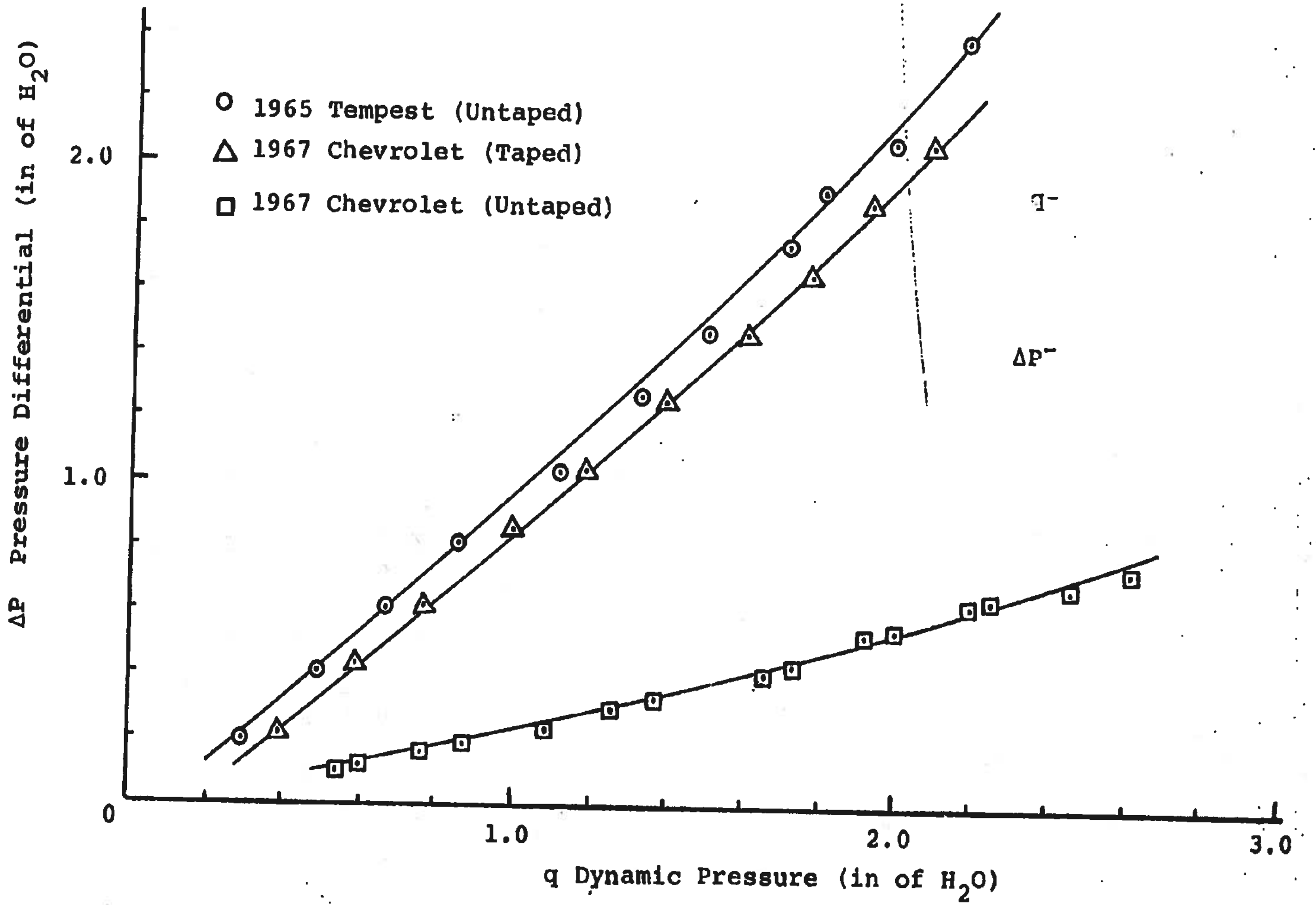

Figure 3.34. ΔP versus q signature plots for 1967 Chevrolet Impala 4-door hardtop and 1965 Pontiac Tempest Custom 4-door sedan.

windows due to the larger values of ΔP_{air}. The question arises as to how much this effect continues at even higher values of ΔP_{air}, beyond the capacity of the 350 CFM blower employed. If the effect continues up to the vehicle over pressures experienced in an actual vehicle submergence, then it would be impossible to correlate the air leak rate tests with the actual water-leak rates because of the different leak conditions involved. For this reason larger capacity blowers with higher delivery pressures were sought to extend the results using the low-capacity blowers up to compartment overpressures of the same order as those occurring during an actual vehicle submergence.

3.2.3.2 Air leak-rate experiments involving high-capacity (1500 CFM) blowers: In order to obtain an estimate of the water-head pressures that occurred during the submergence tests involving the 1967 Chevrolet Impala reported in the earlier study (1), a determination was made using the positions of the vehicle internal and external waterline levels measured during the actual submergence tests of the vehicle. Figure 3.35 shows the results of this determination. The water head of all the vehicle leaks positioned below the internal vehicle waterline would simply be the difference in the two waterline levels at any instant in time during the submergence process. This water head is shown plotted versus elapsed time for the first two submergence tests performed. For the first (unmanned) submergence test performed (in which the leak-rates were the lowest), it appears from the curve that the water-head is quite constant at a value somewhat less than 20 in H_2O. The increase in the measured water-head values after about 50 sec elapsed time is probably due to the accelerated sinking rates when the cowl air-intake grille passed underneath the surface of

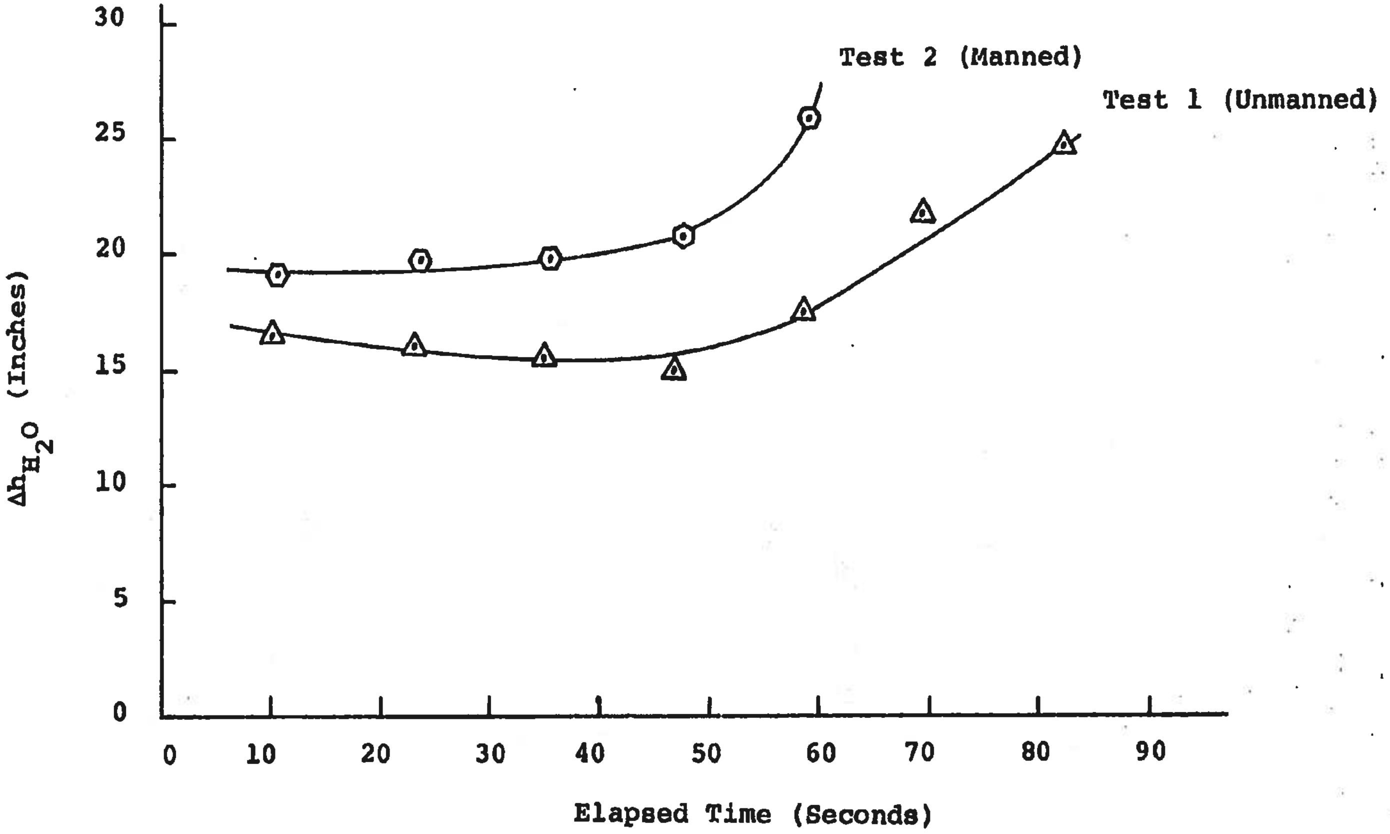

Figure 3.35. Water head of leaks in 1967 Chevrolet Impala measured during submergence tests of March, 1970.

the water. In any event, it appears that the maximum over-pressure of somewhat less than 2 ft H_2O was typical of the first submergence experiment involving the 1967 Chevrolet Impala.

Accordingly, it was concluded that for air leak-rate determination it would be necessary to obtain a blower capable of producing an over-pressure of the same order as that measured in the submergence experiment, i.e., the order of about 1 ft H_2O.

Subsequently, four surplus high capacity blowers were purchased which had been used previously by the U.S. Air Force to evacuate gasoline fumes during fueling operations.

These blowers (USAF MIL-13-7619), manufactured by Blowers, Inc., Blue Island, Ill., had the following delivery pressure--air flow-rate characteristics:

ΔP_{air} (in H_2O)	Q_{air} (CFM)
0	1750
3.5	1500 Nominal rating
6.5	0

By connecting two of the blowers in series the delivery pressure was approximately doubled, allowing a pressure differential of nearly 12 in H_2O to be maintained at significant volume flow rates, due to the flat nature of the ΔP_{air} versus Q_{air} curve in the region of maximum delivery pressure.

Figure 3.33 shows the test set-up involving two of these blowers arranged in series and one of the test vehicles, the 1971 Ford Pinto. In this photograph the 8 in diameter inlet ducting, the 8 in to 5 in diameter discharge ducting, and the pressure measurement instrumentation are shown.

A series of ΔP_{air} versus Q_{air} experiments involving the 1967 Chevrolet Impala and the 1965 Pontiac Tempest (which were tested using the low-capacity blower) were conducted up to the maximum ΔP_{air} that could be maintained with the compounded blower arrangement. In addition, for comparison purposes, two smaller DOT vehicles were tested, one a 1971 Ford Pinto, 2-door sedan, and the other a 1970 American Motors Hornet, 4-door sedan. Prior to the tests a velocity traverse was made of the 8 in diameter exhaust ducting for the determination of the discharge coefficient, C_d, necessary for the determination of the air leak flow-rate, Q_{air}. While the 8 in diameter ducting gave the highest possible pressure differentials, the velocity distribution was of such irregular nature that an 8 in to 5 in reducing section was installed to smooth out the velocity distribution to such an extent that accurate flow-rate measurements could be made.

Also, the same experimental procedure used in the earlier experiments involving the low-capacity blower was followed in these tests. One exception was that it became apparent, during preliminary tests involving the compounded high-capacity blowers, that an internal roof support would be required for the overpressures that could be generated. The roof of the 1967 Chevrolet, which had been depressed during the water submergence tests of March, 1970, was depressed again (after being returned roughly to its original position prior to these tests). Consequently, an extendable rod with pressure distributing pads was used in these tests involving the four vehicles so that permanent roof damage would not be sustained. Figure 3.36 shows the extendable rod in position inside the passenger compartment of the 1971 Ford Pinto.

Figure 3.36. Roof supporting technique used in tests involving high-capacity blowers.

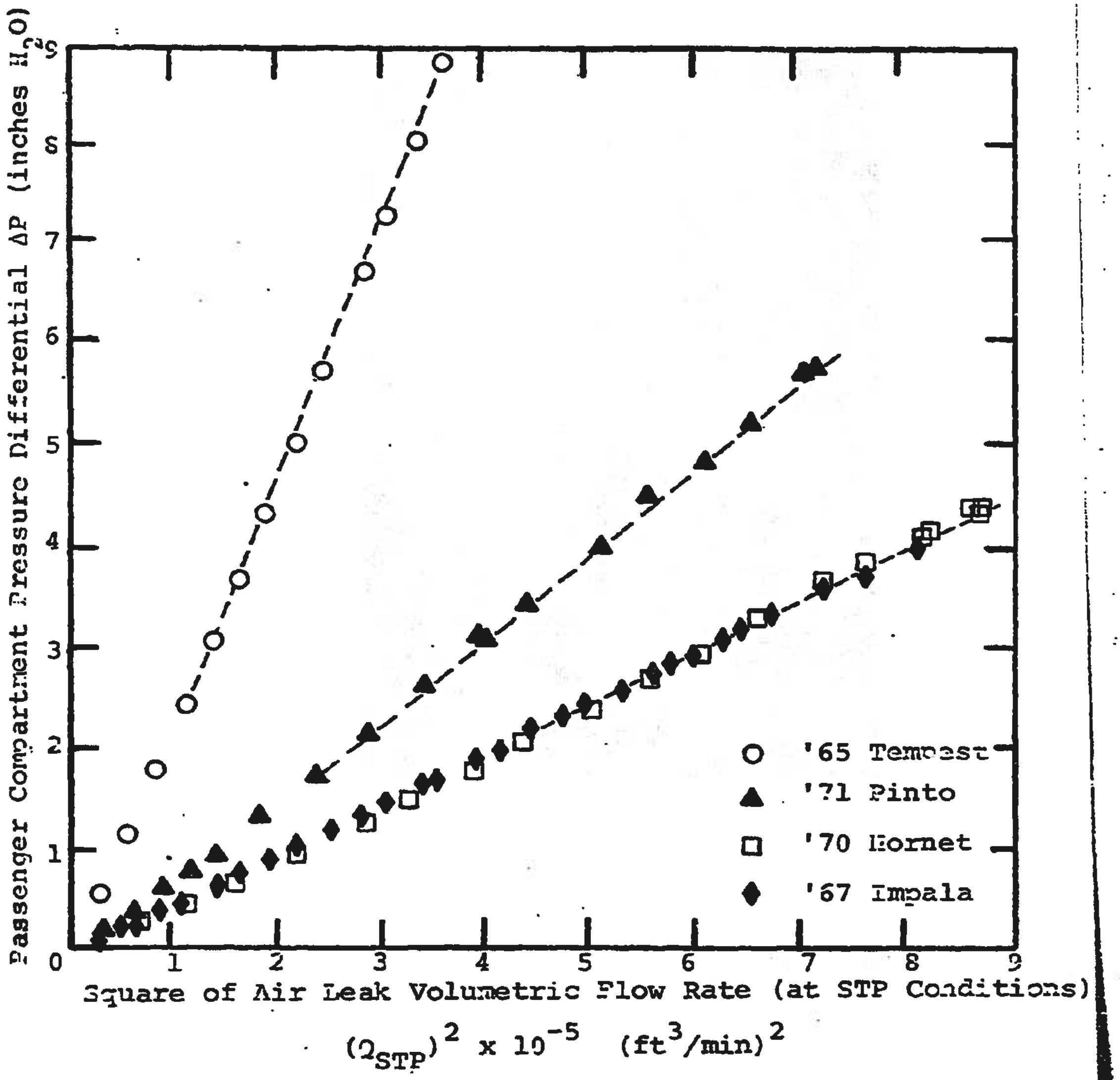

Figure 3.37. Compartment pressure differential versus the square of the air-volume flow-rate for the 1967 Chevrolet Impala.

The results of these experiments are shown in Figure 3.37. In this case, for convenience, the abcissa is shown as the square of the volume flow rate (reduced to standard conditions of the temperature and pressure),* $(Q_{STP})^2$. This procedure was used to compare the slopes of the curves with the theoretical linear prediction while still allowing the determination of Q_{air} from the plots, which would not be possible if the dynamic pressure, q_{air}, is used for the abcissa. Several interesting facts can be determined from the curves.

First of all, all of the four curves show convincing linearity at ΔP_{air} values above 1-2 in H_2O. It was noted in the previous experiments, which were performed using the low-capacity blower, that the largest ΔP_{air} possible was about 2 in H_2O for the 1965 Tempest while all the data recorded for the 1967 Chevrolet Impala was below about 1 in H_2O.

Secondly, the maximum pressure differential measured (about 9 in H_2O for the vehicle with the lowest leak rate) is approaching the value which was desired in the test, i.e., values of the order of 1 ft H_2O to simulate the overpressures of the actual vehicle submergence experiments.

A third observation is the rather unexpected anomoly of a compact 4-door Hornet, with inherently superior door and window sealing properties exhibiting an almost identical ΔP_{air} versus $(Q_{STP})^2$ signature plot throughout the complete range of variables compared to a standard size 4-door hardtop Impala.**

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*29.92 in Hg and 59°F (standard sea level atmospheric conditions).

**An explanation of this anomoly was discovered after the experimental setup was dismantled and the test program was completed. Several large 1 - 1 1/2 in diameter

3.2.3.3 Comparison of theory and experiment: In order to determine the degree of correlation between the water leak flow rate predicted by using the "dry-land" leak-rate simulation method described in the previous section and the leak-rate occurring during an actual vehicle submergence, the following comparisons between theory and experiment will be made:

1. Using the theoretical expression developed in Appendix C-2 relating the measured air flow-rate, Q_{air}, measured in the dry-land leak simulation tests for the 1967 Chevrolet Impala, and the water leak flow rates predicted by theory:

$$\left[\frac{Q_{air}}{Q_{H_2O}}\right]_{\text{theoretical}} = \left[\frac{\rho_{H_2O}}{\rho_{air}}\right]^{1/2} \left[\frac{\Delta P_{air}}{h_{H_2O}}\right]^{1/2} \left[\frac{A_{air}}{A_{H_2O}}\right] \qquad \text{(II-5)}$$

and using the following assumed values for the variables appearing in the relation:

ρ_{H_2O} = 62.4 lb/ft^3 (water density at 70°F)

ρ_{STP} = .0765 lb/ft^3 (air density at 29.92 in Hg and 59°F, i.e., standard atmospheric conditions)

ΔP_{air} = 4 in H_2O (arbitrarily selected in the linear range of the ΔP_{air} versus $(Q_{STP})^2$ signature for the 1967 Chevrolet)

h_{H_2O} = 19 in H_2O (approximate mean water-head obtained from Figure 3.35, Test #1)

A_{air} = A_{H_2O} (assumed here for simplicity)

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holes, normally containing plastic grommets, were discovered in the floor pan of the 1970 Hornet. Perhaps a significant difference in the ΔP_{air} versus $(Q_{STP})^2$ signature would have been effected if these had been discovered and replaced prior to the experiment.

Using the above theoretical expression:

$$\left[\frac{Q_{air}}{Q_{H_2O}}\right]_{theoretical} = 13.1$$

2. Using the experimental measurements made of ΔP_{air} and Q_{air} for the 1967 Chevrolet Impala in the dry-land simulation tests:

   Q_{air} = 898 ft^3/min (obtained from Figure 3.37 at the arbitrary selected P_{air} = 4 in H_2O)

   and using the experimentally determined water leak-rate:

   Q_{H_2O} = 51.6 ft^3/min (deduced from the actual sinking times and vehicle flotation volumes measured for the 1967 Chevrolet

   then, the following ratio, experimentally measured, is:

$$\left[\frac{Q_{air}}{Q_{H_2O}}\right]_{experimental} = 17.4$$

It can be concluded that the theory developed in Appendix C-2 for the predicted value of the water leak-rates in terms of air leak-rates measured in dry-land simulated tests, is in the same order as the measured experimentally from actual submergence tests. In fact the experimentally determined ratio of 17.4 is only 33 percent larger than the ratio of 13.1 predicted by theory. Considering the assumption that the air-leak areas A_{air} (which include the complete vehicle structure in the air-flow experiment) for simplicity was assumed equal to the water leak areas, A_{H_2O}, involved in the submergence process, it appears that the difference is in the correct direction. That is, one would expect the water-leak areas to be somewhat less than the air-leak areas depending upon the initial density of the vehicle (i.e., how much of the vehicle structure is above water during the sinking process).

Also one other consideration is involved. The value deduced for h_{H_2O} from the water-level measurements made during the submergence process (assumed at 19 in H_2O from Figure 3.35) probably is somewhat large. This result, it appears, could be due to the number of leaks occurring above the internal water-level of the vehicle which would tend to reduce h_{H_2O}, the average water-head for all the leaks. It is also noted that this error is in the proper direction tending to increase the theoretically predicted flow-rate of 13.1 more nearly to the measured value of 17.4.

In conclusion, it appears that a quite close correlation exists between the water leak flow-rates actually predicted from theory (using dry-land air leak flow-rate measurements) and the water-leak flow rates actually measured in a vehicle submergence.

Furthermore, the difference predicted in this correlation (33 percent) could be used as an empirical factor, K, defined as follows for the case measured (i.e., the 1967 Chevrolet Impala):

$$K \equiv \frac{[Q_{air}/Q_{H_2O}]_{experimental}}{[Q_{air}/Q_{H_2O}]_{theoretical}} = 1.33$$

It is quite possible that if other model vehicles were tested in both dry-land and submergence experiments that other values of K would be determined depending upon vehicle structural differences and the differences in location of significant leak areas. In this way, the actual water leak-rates for various class and model types could be predicted with a higher degree of confidence throughout the complete vehicle spectrum.

3.2.4 Predicted Vehicle Characteristic Sinking Times for the 1967 Chevrolet Impala, the 1971 Ford Pinto, and the 1970 American Motors Hornet

Making use of elementary hydrostatics employing Archimedes principle, the following expression for the vehicle "characteristic sinking time," t*, in terms of certain specific vehicle properties can be developed (See Appendix C-3 for the development of this expression):

$$t^* = \frac{\dfrac{W_v}{\rho_s} + V_{ia} - \dfrac{W_v}{\rho_{H_2O}}}{\bar{Q}_{H_2O}} \qquad \text{(III-6)}$$

where t^* = characteristic sinking time (min)
W_v = initial vehicle gross weight (lbf)
V_{ia} = initial air-flotation volume inside vehicle passenger and trunk compartments (ft^3)
ρ_s = density of vehicle structure (lbf/ft^3)
ρ_{H_2O} = specific weight of water (lbf/ft^3)
$\bar{Q}_{H_2O}$ = average water leak-rate during the characteristic sinking time (ft^3/min)

Note: The characteristic sinking time is measured from the beginning of the submergence process up to the time the vehicle passes completely under the surface of the water.

It is apparent from the above relation that in order to predict the characteristic sinking time, t*, of a particular vehicle, in addition to the average water leak flow-rate (predicted from air leak flow-rate tests), it would be necessary to obtain the following vehicle properties:

1. W_v--Vehicle gross weight (an easily obtained property)
2. ρ_s--Vehicle structural specific weight. From the knowledge of the weight breakdown of the various structural materials making up the vehicle the density can be obtained. It is noted that since steel comprises the majority of the structural material of the average vehicle the value of ρ_s should approach that of steel, i.e., 780 lbf/ft^3.
3. V_{ia}--Vehicle initial air-flotation volume. The total air-volume contained in a typical vehicle is comprised mainly of the volume of the passenger and trunk compartments.

Using the value for V_{ia} as measured for the 1967 Chevrolet and reported in the following section (3.2.5) of this report, a determination of the characteristic sinking time, t*, can be made for this vehicle and compared to the actual sinking time observed during the submergence tests.

Using the following assumed values:

W_v = 4230 lbf (measured on scales)

V_{ia} = 176.1 ft^3 (measured from O_2 concentration experiment)

$\frac{W_v}{\rho_s}$ = 5.4 ft^3 (for ρ_s = 780 lbf/ft^3)

ρ_{H_2O} = 62.4 lbf/ft^3 (specific weight of H_2O at 70°F)

and using a value for $\bar{Q}_{H_2O}$ = 70.1 ft^3/min where this value can be obtained from the theoretically predicted leak-rate ratio at a particular air-leak flow-rate measured at a given pressure differential ΔP_{air} (obtained during the dry-land simulation tests as reported in the previous section).

$$\left[\frac{Q_{air}}{Q_{H_2O}}\right]_{theoretical} = 13.1$$

for $\Delta P_{air} = 4.0$ in H_2O and $Q_{air} = 898$ ft^3/min.

Thus, $\bar{Q}_{H_2O} = Q_{air} / \frac{Q_{air}}{Q_{H_2O}}_{theoretical} = \frac{898}{13.1} = 68.5$ ft^3/min

Using the above values for the vehicle properties of interest in the expressions for t* (Equation III-6):

$$t^* = \frac{5.4 + 176.1 - \frac{4230}{62.4}}{68.5} = \frac{113.6}{70.1}$$

or

$$t^* = 1.62 \text{ min } (99.5 \text{ sec})$$

This value compares with the value of 132 sec (2.2 min) actual sinking time recorded for the first (unmanned) submergence test made using this vehicle in March, 1970. As expected from the analysis, the ratio between the actual sinking time and the characteristic time, t*, predicted for this vehicle is:

$$\frac{t}{t^*} = \frac{2.2}{1.66} = 1.33$$

This value agrees with the prediction in the previous section of the report (3.2.3) for the ratio of the experimental to the theoretically predicted leak flow-rates.

The same reasoning can be applied to the use of the predicted characteristic sinking times, t*, of a given vehicle as was done for the leak rates in the previous section (3.2.3). Moreover, it appears that these sinking times have a much more practical meaning than the leak flow-rates when comparing the submergence characteristics of various vehicles.

A comparison can be made of the characteristic sinking time predicted for the 1967 Chevrolet and two other vehicles. The air-flotation volumes of these vehicles were measured by means of the gas-concentration method and are reported in the next section (3.2.5).

Therefore, making use of the following measured values for the flotation volumes, the reported gross weights and the predicted water leak flow rates, Q_{H_2O}, for the vehicles of interest* and using the same assumed value for the vehicle structural density (ρ_s = 780 lbf/ft^3) as was used earlier for the 1967 Chevrolet, Equation III-6 can be solved for t* to obtain:

t* = 88 sec (1971 Ford Pinto)

t* = 70 sec (1970 American Hornet)

---

*The predicted water leak flow rates were determined by use of the correlation plots of ΔP_{air} vs $(Q_{STP})^2$ appearing in Figure 3.37 at a ΔP_{air} = 4 in H_2O as in the case of the 1967 Chevrolet. Also, use was made of the theoretical relation $\left[\frac{Q_{air}}{Q_{H_2O}}\right]_{theoretical}$ = 13.1 presented in the previous section, with h_{H_2O} = 19 in H_2O and ΔP_{air} = 4.0 in H_2O which was also assumed for the case of the 1967 Chevrolet.

where:

	V_{ia} (ft^3)	W_v (lbm)	$\bar{Q}_{H_2O}$ (ft^{3}min)	Q_{STP} (ft^3/min)
1971 Ford Pinto	106.3	2015	54.0	707
1970 American Hornet	118.4	2814	67.8	889

These characteristic sinking times can be compared with the value predicted for the 1967 Chevrolet Impala:

t* = 99.5 sec (1967 Chevrolet Impala).

Some significant conclusions can be drawn:

1. First, the characteristic sinking times for both vehicles are lower than for the case of the 1967 Chevrolet, i.e., for the 1971 Ford Pinto the predicted time is about 85 percent, and for the 1970 American Hornet the predicted time is about 68 percent of the time predicted for the 1967 Chevrolet Impala.
2. This result probably would be anticipated for the 1970 Hornet since the ΔP_{air} versus $(Q_{STP})^2$ signature for the vehicle is almost identical to the 1967 Chevrolet while the air-flotation volume is considerably less (see Figure 3.37).
3. This result probably would not be anticipated for the 1971 Ford Pinto since its ΔP_{air} versus $(Q_{STP})^2$ signature indicates considerably lower leak rates than the 1967 Chevrolet. The dominating vehicle property here, however, is the low air-flotation volume (106.3 ft^3) appearing in the numerator of the expression for t*.

In conclusion, it appears that even though only four vehicles could be tested using the "dry-land" vehicle air leak-rate tests to determine the ΔP_{air} versus $(Q_{STP})^2$

signatures, significant differences in the leak-rate characteristics were predicted which led to corresponding differences in the vehicle characteristic sinking times.*

3.2.5 Measurement of Vehicle Flotation Volumes

In order to predict the vehicle characteristic sinking times as determined in the previous section (3.2.4) one critical vehicle property was required, i.e., V_{ia}, the air-flotation volume, which for the average passenger vehicle is comprised mainly of the combined volume of the passenger and luggage compartments.

Accordingly, early in the study, letters were sent to the three large automotive companies inquiring as to the availability of figures for the volumes of interest in particular for those vehicles which had been tested to the present studies.

Only two replies were obtained:

1. S. C. Gullo, Research Contracts, General Motors Environmental Activities Staff
2. R. E. Kimball, Executive Engineer, Safety Planning, Ford Motor Company

Mr. Gullo indicated that with one exception none of the GM divisions were making any volumetric measurements or calculations at the present time. He mentioned that although in past years the AMA specifications showed some of the volumes of interest, this type of data was dropped more recently because it was found that the data was largely inaccurate.

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*It is noted here that the characteristic sinking time of the 1965 Pontiac Tempest, which showed the lowest predicted leak-rate of the four vehicles, was not included because the air-flotation volume of the vehicle was not measured. This was primarily due to the lack of time available and other technical difficulties.

The recent exception was some measurements made by the Buick Motor Division of the luggage compartment volumes of some of their 1971 models by filling the luggage compartment with small solid particles of polyethylene or polypropylene. The volume occupied by the plastic was later measured by some convenient means after all of it was removed from the luggage compartment.

Mr. Kimball of Ford Motor indicated that the volume figures that were requested were not available in a form usable for flotation purposes. That is, the design procedure followed by Ford is based upon performance oriented parameters such as control reach requirements, occupant head clearance needs, etc., which do not yield accurate volumetric data.

From the lack of available data of any kind, it was concluded that measurement techniques should be attempted, with the main criterion that the method developed be of reasonable accuracy, i.e., ± 10 percent, and be rapid, convenient, and not require highly skilled personnel or extensive expensive instrumentation.

It appeared that two techniques were applicable, both involving the measurement of the gas volume occupying the flotation volumes of interest, i.e., the passenger and luggage compartments.

<u>3.2.5.1 The positive displacement balloon method</u>: The initial method that was investigated utilized either 600 gm or 1200 gm weather balloons capable of being inflated with air so as to conform as closely as possible to the inner surface of the two large vehicle air spaces, i.e., the passenger and luggage compartments.

The total air volume passed into the balloons was measured by means of a "Precision" Sargent wet-test meter manufactured by the Precision Scientific Company, Chicago, Illinois (Model 3110). The maximum "flow rate" capacity of this meter is 20 ft^3/hr at 1/10 ft^3 per revolution of the dial. The pressure and temperature of the metered air was measured by a water manometer and mercury thermometer attached to the meter. The accuracy of the meter is listed as within 0.5 percent of the 1/10 ft^3 reading. The indicated air-volumes were corrected to the pressure and temperature readings recorded for the air occupying the balloon volume within the vehicle. These corrections were normally very small, depending mainly upon the variation of the air temperature during the experiment.

The results of two tests for the measurement of the passenger compartment volume and one test for the measurement of the luggage compartment volume are shown in Table 3.18.

The method is straightforward, but it has three fundamental disadvantages:

1. A long time (7-1/2 hr in this case) is required to pass the total vehicle air volume at the maximum rate dictated by the instrument used (20 ft^3/hr).
2. The very delicate nature of the balloon material (natural rubber) required careful taping of all sharp interior surfaces of the vehicle to insure the balloon did not develop leaks. This procedure was particularly tedious in the roof area where the head-liner had been removed, and in the luggage compartment with its many sharp structural surfaces.
3. Also, characteristic of this method was that a certain unavailable volume (composed mainly of the space under the instrument panel and certain recesses in the luggage compartment) could not be measured without locally distending the balloon in these areas causing it to burst. For this reason the values presented in Table 3.18 represent a lower bound to the actual vehicle volume. That is, the total volume cannot be lower than

TABLE 3.18

MEASURED PASSENGER AND LUGGAGE COMPARTMENT VOLUME OF THE 1967 CHEVROLET IMPALA EMPLOYING THE POSITIVE DISPLACEMENT BALLOON METHOD*

Test Number	Passenger Compartment Volume (ft^3)	Luggage Compartment Volume (ft^3)
1	119.4**	
2	117.1	
3		34.4

*Test #1 using 2 - 600 gm weather balloons.
Test #2 using 2 - 1200 gm weather balloons.
Test #3 using 1 - 600 gm weather balloon.
Air volume measurements made using Precision Sargent wet-test meter.

**Total Volume V_T = 119.4 + 34.4 = 153.8 ft^3 using the largest measured value of the passenger compartment (Test #1).

these values. Therefore, the lower bound for this vehicle's total vehicle compartment volume would be that value associated with the maximum recorded for the passenger compartment, 119.4 ft^3, plus the luggage compartment volume, giving the following total volume:

$$V_T = 153.8 \ ft^3$$

3.2.5.2 The gas concentration method: The method is based on the perfect gas law for mixtures and is explained in detail in Appendix C-4.

The method consists of measuring accurately the volume of a test gas (non-reactive with O_2) which is passed into a balloon and then suddenly released into the total volume. Two cases are of interest.

1. If the test gas is either molecular oxygen (O_2) or nitrogen (N_2) and if some instrumentation is available to measure the initial and final concentration of the oxygen or nitrogen in the mixture, then the following relations apply for the determination of the total volume, V_T, occupied by the gas mixture for O_2 as a test gas:

$$V_T = \frac{V_B \left[1 - (X_{O_2})_i\right]}{(X_{O_2})_f - (X_{O_2})_i}$$

where $(X_{O_2})_i$ and $(X_{O_2})_f$ = initial and final measured O_2 concentrations (by volume) respectively; and for N_2 as a test gas:

$$V_T = \frac{V_B \ (X_{O_2})_i}{(X_{O_2})_i - (X_{O_2})_f}$$

The above relations are valid if the pressure and temperature of the test gas in the balloon are the same as the pressure and temperature of the final gas mixture. If this condition does not hold, the correction factors shown in Appendix C-4 must be applied.

2. If the test gas is neither molecular O_2 nor N_2 (e.g., CO_2) and some instrumentation for the measurement of the final concentration of this test gas is available then the following relation applies for CO_2 as the test gas, for example:

$$V_T = V_B \left[\frac{1}{X_{CO_2}}\right]$$

(a) <u>Method employing the Beckman-O_2 analyzer using continuous sampling</u>--This method utilizes the Beckman-O_2 Analyzer (Model F-3) manufactured by the Beckman Instrument Co., Fullerton, California. The instrument has an advertised accuracy of ± 1 percent of full scale reading. The instrument is calibrated at the zero end of its scale by use of a zero gas (N_2 in this case) and near the full scale point (25 percent O_2) by the use of air (21 percent O_2) as the span gas.

The volume of the test gas contained in the balloon (nominally 30 ft^3 contained in a 300 gm weather balloon) is measured by means of the "Precision" Sargent wet-test meter described in the previous section (3.2.5.1).

Two tests were performed utilizing oxygen as the test gas in the balloon. The test arrangement showing the 1967 Chevrolet test vehicle and the instrumentation involved in the tests is shown in Figure 3.38. The experimental procedure for both of these tests consisted of introducing nitrogen into the vehicle passenger compartment. The addition of the nitrogen to the atmospheric air (21 percent O_2 by volume) into the passenger and trunk compartments was made because the maximum concentration of O_2 that could be recorded by the Beckman O_2 analyzer (25 percent O_2) restricts the accuracy of the measured vehicle volume, V_T. This limitation can be seen by examining the denominator of the first expression given for V_T, containing the difference between the final and initial concentrations of oxygen.

Prior to the experiments, the vehicle's seats and the fiberboard panel separating the passenger and luggage compartments had been removed. A 20 in diameter window fan was situated at one side of the opening between the two compartments so that a circular flow pattern was established insuring rapid mixing the gases in the two compartments. When the initial O_2 concentration was measured at about 3-4 percent as recorded on a Speedomax recorder, the balloon was broken and the fan was run intermittently for Test 1 and continuously for Test 2.

Facsimiles of the Speedomax records are shown in Figures 3.39 and 3.40 for Test 1 and Test 2 respectively.

Table 3.19 lists the results of these two tests employing O_2 as the test gas. The corrected total vehicle volume for the second

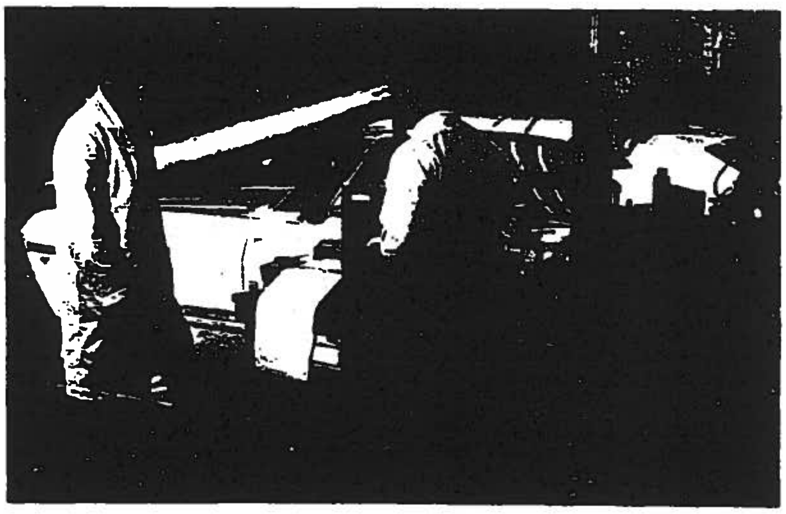

Figure 3.38. Photograph of the 1967 Chevrolet Impala showing test arrangement for the vehicle flotation volume measurement using the Beckman O_2-analyzer.

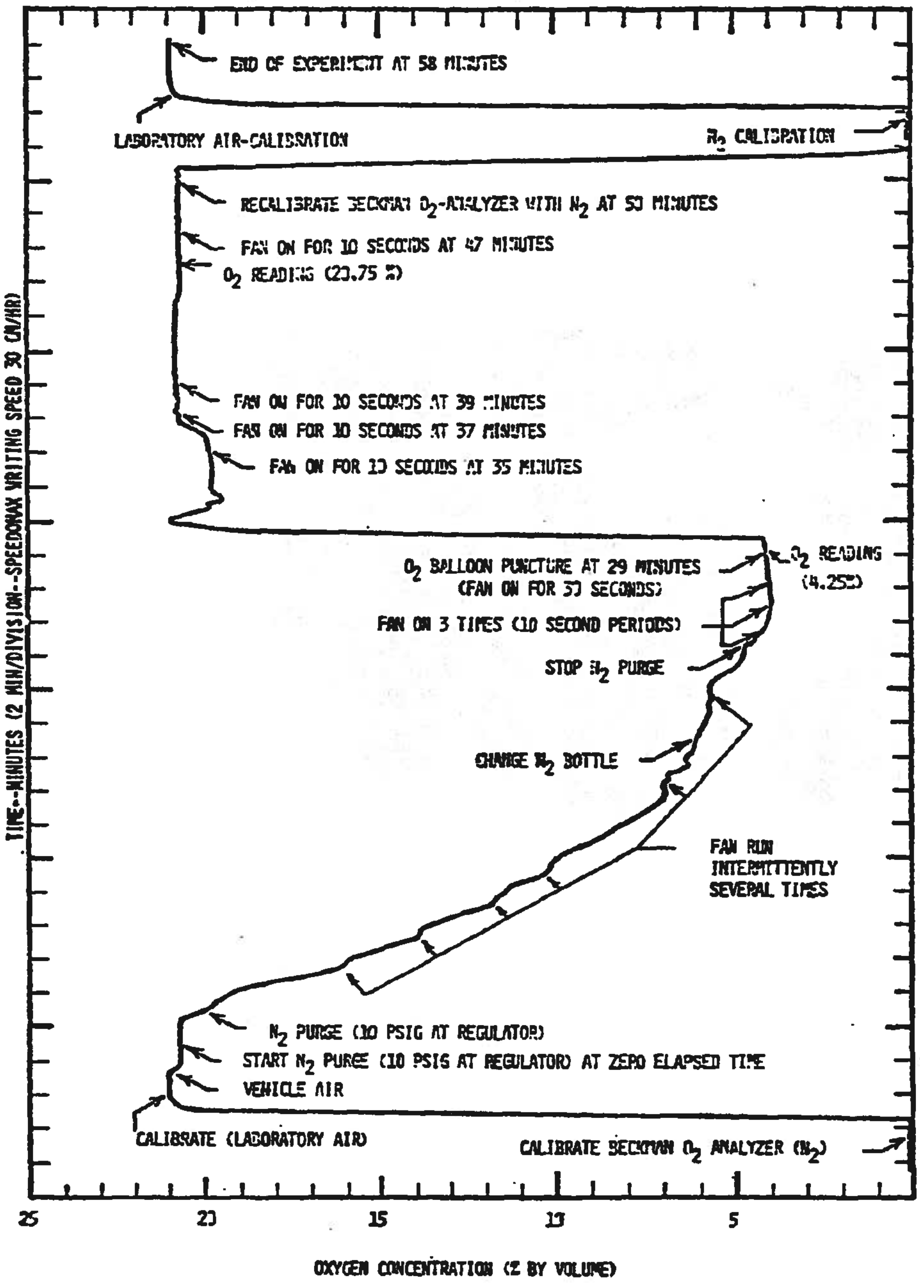

Figure 3.39. Speedomax recording of the O_2 concentration in the 1967 Chevrolet Impala measured by the Beckman O_2-Analyzer (Test #1).

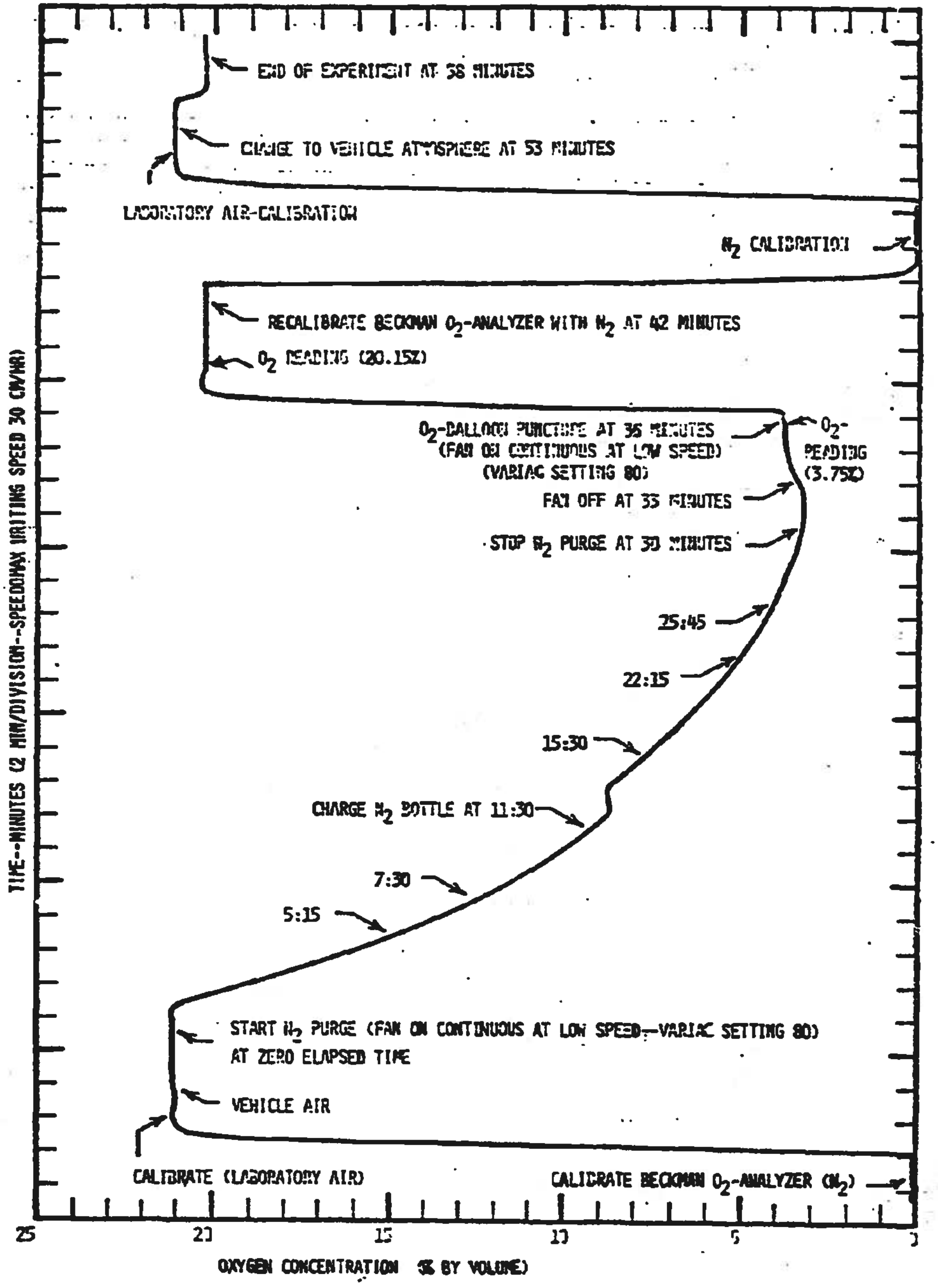

Figure 3.40. Speedomax recording of the O_2 concentration in the 1967 Chevrolet Impala measured by the Beckman O_2-Analyzer (Test #2).

TABLE 3.19

MEASURED PASSENGER AND LUGGAGE COMPARTMENT VOLUME OF THE 1967 CHEVROLET IMPALA USING THE BECKMAN O_2 ANALYZER*

Test Number	Balloon Gas	V_B Balloon Volume (Corrected) ft^3	$(X_{O_2})_i$ Initial O_2 Concentration (Volume Percent)	$(X_{O_2})_f$ Final O_2 Concentration (Volume Percent)	V_T Total Volume (at Lab Atm Conditions) ft^3
1	O_2**	30.48	4.25	20.75	176.9
2	O_2	29.88	3.75	20.15	175.3
3	CO_2**	29.66	21***	17.9	165.7
4	CO_2	30.22	21***	17.8	170.0

*Beckman O_2 Analyzer calibrated by using air (O_2 = 21%) and pure N_2 (O_2 = 0%).

**Purity of test gases - 99.5%.

***Atmospheric O_2 assumed 21% by volume for these experiments.

test (175.3 ft^3) where continuous mixing was employed (with the fan running at a continuous low speed so the vehicle air-leaks were minimized but efficient mixing was effected) is slightly lower than the total vehicle volume (176.9 ft^3) recorded for the first test where intermittent fan operation at high speeds was used as the gas mixing method. It is believed that this value for the second test is somewhat more accurate because of the more efficient mixing method employed. However, since it represents only about a one percent difference in the higher value, the simple arithmetic average of V_T = 176.1 ft^3 will be used for the total vehicle volume as measured by the O_2 addition method.

Two other tests were performed each utilizing CO_2 as the test gas in the balloon. These tests were made primarily to determine the suitability of the use of a gas other than N_2 or O_2, and to determine if the results checked the volume measurement made using oxygen as the test gas. The same procedures were used for mixing as that which was employed in tests 1 and 2. In this case, Test 3 utilized intermittent mixing while Test 4 utilized continuous mixing. For both these tests involving CO_2 as the test gas no nitrogen addition was required because the accuracy of the final measured volume would not be improved in this case. Therefore, atmospheric air (21 percent O_2 by volume) was used as the initial gaseous mixture for convenience reasons.

The Speedomax records for Tests 3 and 4 are shown in Figures 3.41 and 3.42 respectively.

For the case of Test 3, where intermittent mixing was utilized, an oscillatory reading of the measured O_2 concentration was recorded in phase with the operation of the fan. This characteristic is quite certainly due to the large difference in molecular weight (44 lb/lb-mole) of the test gas, CO_2, compared to air (29 lb/lb-mole). In the periods of quiescence inside the compartment, the CO_2 (the denser gas) begins to settle to the bottom of the vehicle giving erroneously higher values of O_2 concentration. For the case of Test 4, where continuous mixing was utilized, an almost constant O_2 concentration was recorded for about six minutes (actually increasing slightly due to slight compartment leaks).

Table 3.19 also lists the results of these two tests employing CO_2 as the test gas. From the final O_2-concentration measurements made for these tests, the final concentration of the CO_2 can be easily calculated (in this case assuming that the ratio of O_2 to N_2 remains the same). Then the second relation involving V_T is used for the calculation of the total gas volume, i.e., use is made of:

$$V_T = V_B \left[\frac{1}{X_{CO_2}}\right]$$

It is noted that for Tests 3 and 4, somewhat lower values of V_T are recorded than the values recorded using O_2 as the test gas. In this

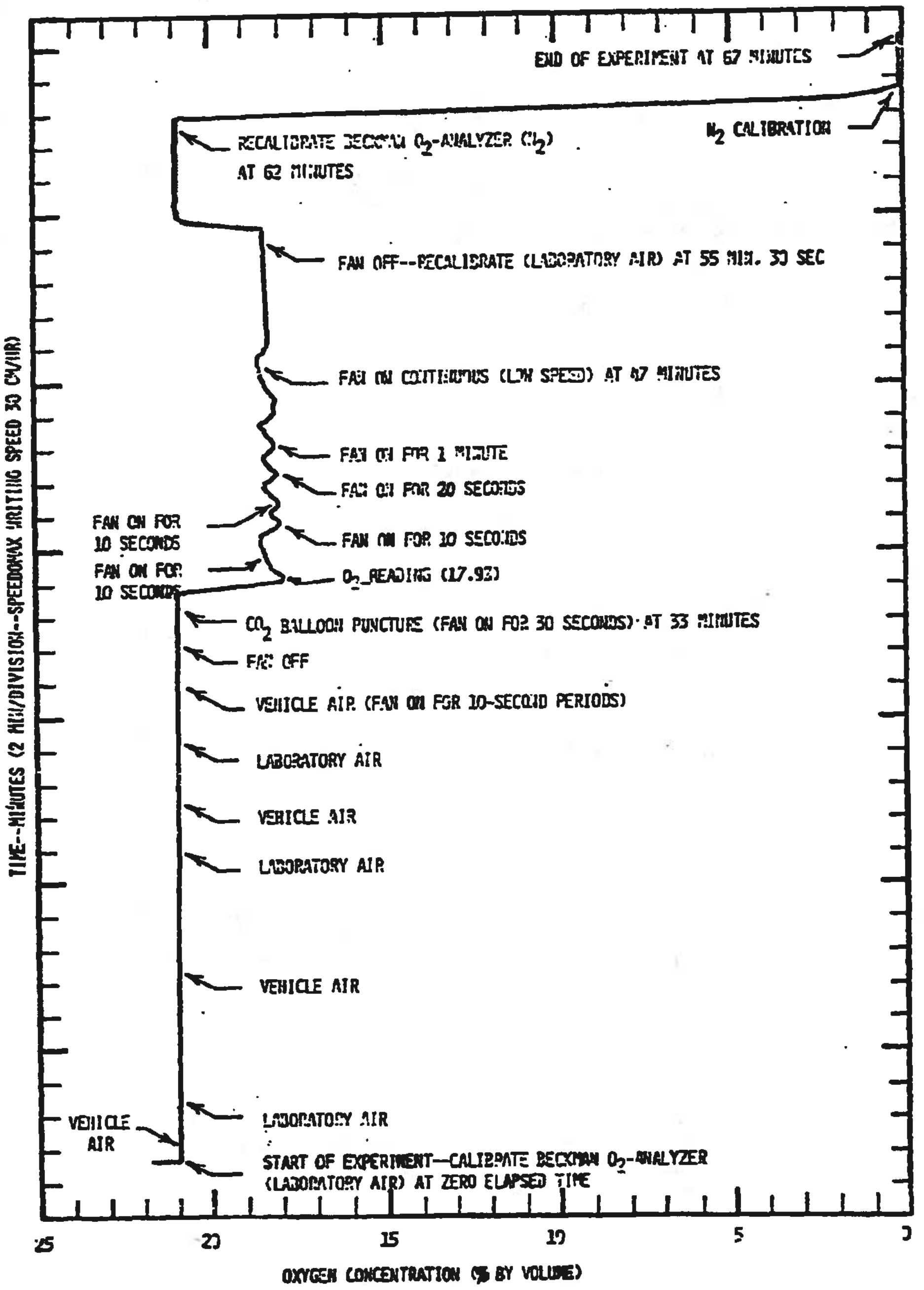

Figure 3.41. Speedomax recording of the O$_2$ concentration in the 1967 Chevrolet Impala measured by the Beckman O$_2$-Analyzer (Test #3).

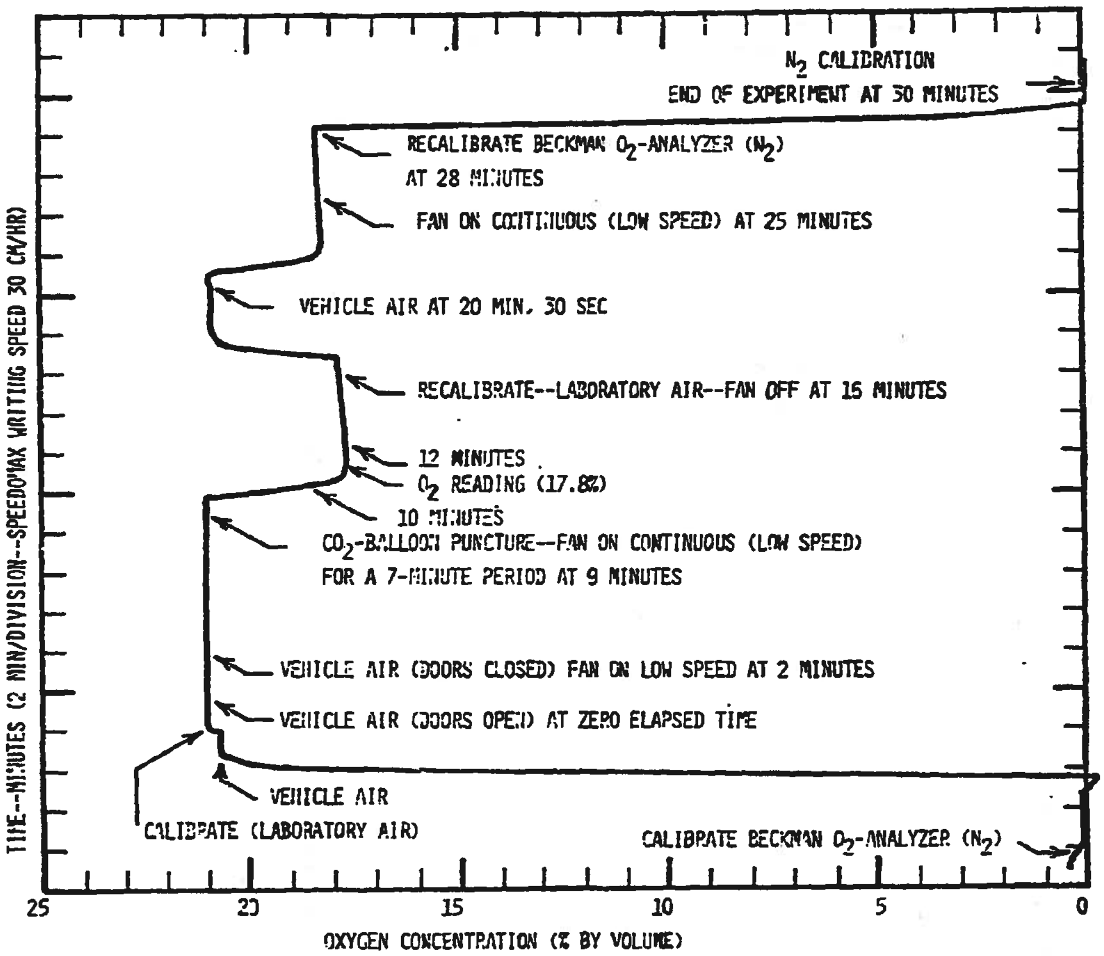

Figure 3.42. Speedomax recording of the O_2 concentration in the 1967 Chevrolet Impala measured by the Beckman O_2-Analyzer (Test #4).

case a more significant difference is recorded for the case of continuous mixing versus intermittent mixing. It appears that the more accurate value would be that recorded in Test 4 (170.0 ft^3) which more closely checks the values recorded using O_2 as the test gas. The lower value of V_T (165.7 ft^3) which was recorded for Test 3 is probably in error due to the more inefficient mixing scheme used.

In conclusion, it appears that a value of about 176 ft^3 quite closely approximates the total internal air-volume of the trunk and passenger compartment for the 1967 Chevrolet Impala tested. This figure is slightly higher than the value of 170 ft^3 which was measured using CO_2 as the test gas where inaccuracy due to settling of the test gas was minimized by continuous mixing.

It is believed, then, that this higher figure (176 ft^3) can be used as an accurate datum for the comparison of a simpler gas sampling method where a batch-sample is used rather than the continuous sampling accomplished using the Beckman O_2 analyzer.

(b) Method employing the Kitigawa gas sampler using batch-sampling--A series of experiments involving the use of a simple gas sampler for batch sampling was conducted using three test vehicles: the 1967 Chevrolet Impala (for a check with the more accurate results employing the Beckman O_2 analyzer) and two other test vehicles: the 1971 Ford Pinto 2-door sedan and the 1970 American Hornet 4-door sedan. These vehicles were chosen so that the total air-flotation volumes could be obtained, allowing the characteristic sinking times (reported in the previous section (3.2.2.4)) for these vehicles to be calculated.

The instrumentation involved the use of the Precision Sargent wet-test meter which was employed in the previously described experiments for the measurement of the volume of the test gas.

The gas sampler used for these experiments was the Kitigawa (Model 400) gas sampler employing a small CO_2 sensing capsule containing a color sensitive resin. Figure 3.43 shows the sampler and one of the unused tubes placed on a nomograph used for the determination of the CO_2 concentration by the measurement of the length of the stained section of the resin.

The experimental procedure consisted of measuring the volume of CO_2 which passed through the wet-test meter by inflating a small balloon to a sufficient volume (somewhat less than one cubic foot) so that after the balloon was broken the final concentration measured by the instrument was not higher than the maximum (0.7 percent CO_2) which could be recorded by the capsules used (low-range CO_2 detector tube type 126-b).

In all cases for those experiments involving CO_2, continuous mixing of the gaseous mixture after the balloon was burst and during the sampling period (5-6 min) was employed. A period of one min was allowed between the time the balloon was broken until the beginning of the sample to allow sufficient mixing.

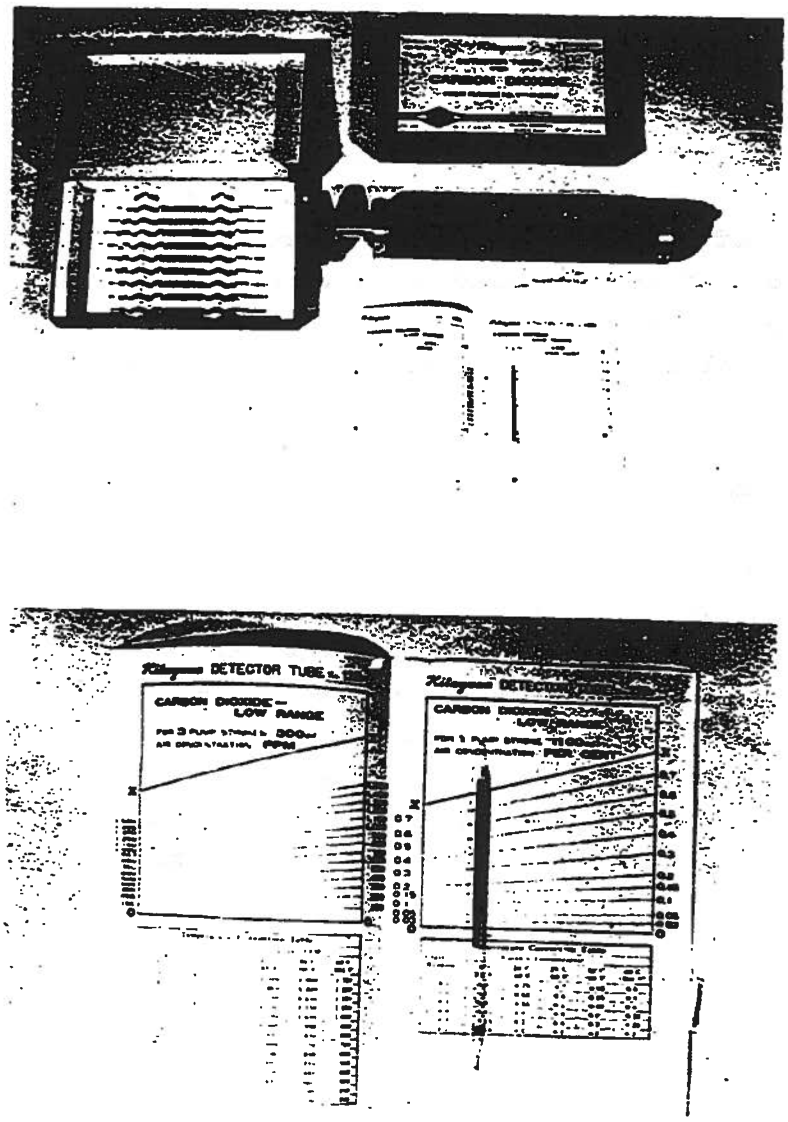

Figure 3.43. Photograph of Kitigawa Precision Gas Sampler with sample tube and nomograph.

This period was selected by observing the time required for complete mixing of CO_2 from the Speedomax records of Tests 3 and 4 made using the Beckman O_2 analyzer and discussed in the previous section. A mixing period longer than one minute was not employed because of the compartment leak errors which were noticed in the Speedomax recordings for these previous experiments.

Table 3.20 shows the results of these tests. In all, 15 tests were performed; five for the 1967 Chevrolet Impala, five for the 1971 Ford Pinto, and ten for the 1970 American Hornet. The additional five tests on the Hornet were conducted to determine whether any significant difference could be detected if the test gas volume was increased or decreased a significant amount, producing readings at the high and low end of the CO_2-concentration scale of the nomograph.

The arithmetic mean of the tests show that the total gas volume calculated by making use of the second expression for V_T, i.e.:

$$V_T = V_B\left[\frac{1}{X_{CO_2}}\right]$$

for the three vehicles tested is as follows:

1.	1967 Chevrolet Impala	163.9 ft^3
2.	1971 Ford Pinto	106.3 ft^3
3.	1970 American Hornet	118.4 ft^3

The maximum test variation recorded for each vehicle is:

TABLE 3.20

MEASURED PASSENGER AND TRUNK COMPARTMENT VOLUMES OF THE 1967 CHEVROLET IMPALA, THE 1970 FORD PINTO AND THE 1970 AMERICAN HORNET USING THE KITIGAWA PRECISION GAS DETECTOR

Vehicle	Balloon Gas	V_B Balloon Volume (ft^3)	X_{CO_2} Measured CO_2 Concentration (Volume Percent)	V_T* Total Volume (at Lab Atm Concitions	$\bar{V}_T$ (Arithmetic Mean (ft^3)
1967 Chevrolet	CO_2	0.80	0.51	160.82	163.91
		0.80	0.49	167.31	
		0.80	0.49	167.18	
		0.80	0.49	166.39	
		0.90	0.58	157.83	
1970 Pinto		0.50	0.45	112.56	106.30
		0.50	0.47	107.62	
		0.50	0.49	103.18	
		0.50	0.48	105.29	
		0.502	0.50	102.86	
1970 Hornet		0.50	0.48	106.96	118.37
		0.50	0.45	113.56	
		0.50	0.43	119.14	
		0.50	0.38	134.42	
		0.50	0.435	117.66	
		0.75	0.68	111.50	
		0.75	0.63	121.16	
		0.75	0.61	125.21	
		0.25	0.215	118.56	
		0.25	0.22	115.55	

*V_T corrected volumes obtained by using measured balloon gas pressure and temperature (P_B and T_B) and final mixture pressure and temperature (P_f and T_f) and using relation developed for V_T (Equation IV-14 in Appendix C.4).

1.	1967 Chevrolet Impala	± 3%
2.	1971 Ford Pinto	± 2.5%
3.	1970 American Hornet	± 7.5% (disregarding 5th test)

The statistical accuracy of these readings is well within the advertised accuracy of ± 10 percent. The reason for the greater scatter in the experiments with the 1970 Hornet is not apparent. Perhaps a larger sampling number would give even larger maximum and minimum deviations from the mean value so as to approach the advertised accuracy of ± 10 percent.

In conclusion, the batch gas sampling technique, when using a gas sampler of similar accuracy, provides a convenient, simple method of determining the interior vehicle volumes of interest, without requiring instrumentation of significant cost. A simple fan for mixing, a means of measuring the test gas volume, and a comparable batch-type gas sampler is all that is required.

The degree of the accuracy of the batch-sampling method shows that an error of about 7 percent was made in the mean air-volume measurement (163.9 ft^3) for the five tests involving the 1967 Chevrolet compared to the more precise value of 176.1 ft^3 measured by the more sophisticated instrumentation (the Beckman-O_2 Analyzer). This accuracy, it is believed, is sufficient for the determination of the vehicle air-flotation volume allowing the prediction of the vehicle characteristic sinking time to the order of the accuracy of the assumptions made in the analysis.

3.2.6 General Discussion and Status of Related Studies

3.2.6.1 Increase of vehicle sinking times by reduction in water leak rates: Some of the results of the previous sections related to the predicted sinking times of automotive vehicles can be applied to the development of performance specifications for the automotive industry to enhance the passenger escape probabilities in a submergence-type accident. It is apparent that the characteristic sinking time, t*, needs to be increased in order to allow the maximum possible time for vehicular escape or rescue through window openings while these openings are still at least partially above water. It is noted that this mode of escape from a submergence-type accident was the only practical method concluded from the results of the previous study (1).

In order to define some criterion which would allow an orderly escape or rescue operation, an elapsed time of ten minutes is set arbitrarily to represent a period of time sufficient for the passengers to overcome the physical and psychological shock of an initial vehicle submergence and to make their escape through one of the window openings.

On the basis of the actual submergence characteristics of the 1967 Chevrolet Impala recorded in the submergence tests of March 1970, approximately one-half of the overall sinking time had elapsed before the external water line reached above the lower front corner of the front windows. For the case of the 1967 Chevrolet this period of time amounted to slightly more than one min with a total sinking time of 2.2 min. If other vehicles behave similarly, then based on the arbitrarily set escape time of 10 min, a characteristic sinking time, t*, of 20 min would be required for every vehicle.

The predicted characteristic sinking time of 99.5 sec, calculated for the 1967 Chevrolet in Section 3.2.4 will be used as the basis for determining the required changes in the water-tight integrity in order to allow a predicted sinking time of 20 min for this vehicle. Using Equation III-6 for t* developed in Appendix C.3, and with the same vehicle characteristics (W_v, V_{ia}, ρ_s) as used previously, the average water leak flow rate, $\bar{Q}_{H_2O}$, for the assumed t* of 20 min is:

$$\bar{Q}_{H_2O} = \frac{113.6}{20} = 5.68 \text{ ft}^3/\text{min}$$

Then using the expression developed previously,

$$\bar{Q}_{H_2O} = \frac{Q_{air}}{(Q_{air}/Q_{H_2O})_{theoretical}}$$

and solving for Q_{air} using the value of:

$$(Q_{air}/Q_{H_2O})_{theoretical} = 13.1$$

which was previously calculated for this vehicle, then:

$$Q_{air} = (5.68)(13.1) = 74.4 \text{ ft}^3/\text{min}$$

This represents the air leak flow rate, measured in a dry-land leak rate simulation experiment (at a ΔP of 4 in H_2O): the leak-rate required to allow a characteristic sinking time, t*, of 20 min. Note that this time corresponds to an air leak flow rate which is 74.4/898 = .083 or about 8 percent of the measured air leak flow rate for this vehicle in its initial condition.

It is interesting to speculate whether this reduction in the leak rate of this vehicle could be effected by more efficient sealing techniques in the location of the significant leak areas below the approximate position of the vehicle's initial waterline. It was noted that inherently inferior seals around the doors and windows contributed largely to the significant differences in leak rates measured in this vehicle and in the 1965 Pontiac Tempest. It was also noted that the simple taping scheme applied to the 1967 Chevrolet Impala resulted in a reduction of nearly 50 percent compared to the vehicle's leak rate in an untaped condition. While the change would nearly double the predicted sinking time (to approximately 200 sec), an additional air-leak reduction factor of about 6 would be necessary to arrive at an air leak flow rate of 74.4 ft^3/min required to allow a predicted characteristic sinking time, t*, of 20 min.

It is apparent, however, that the overall water tight integrity of the 1967 Chevrolet Impala hardtop does not represent the more typical 4-door family sedan with its inherently more superior sealing system around the doors and windows. For this reason it would seem to be more logical to use the measured air leak flow-rate characteristics of the 1965 Pontiac Tempest (a more representative type of average passenger vehicle) as a basis for determination of the required changes necessary in a typical vehicle's water tight integrity to allow a characteristic sinking time of 20 min.

In order to accomplish this, the following estimates for the vehicle characteristics necessary for the calculation of t* will be made.

Assume for the 1965 Pontiac Tempest, 4-door sedan the following values:

Total weight, W_v = 3050 lb (6 cylinder engine)

Total air volume, $V_T = 150\ \text{ft}^3$ (assumed in between the values of $118\ \text{ft}^3$ and $176\ \text{ft}^3$ measured for the 1970 Hornet and the 1967 Chevrolet respectively)

Further assume the same average water head and the same pressure differential $\Delta P_{air} = 4$ in H_2O. This yields the same value of:

$$(Q_{air}/Q_{H_2O})_{\text{theoretical}} = 13.1$$

which was used previously. Now, in order to determine the predicted characteristic sinking time for this vehicle, the cases for the vehicle in the conditions shown in Table 3.17 will be determined.

a) Initial condition (windows and kick vents closed, air intake open)--From the graph of ΔP_{air} versus $(Q_{STP})^2$ for this vehicle shown in Figure 3.37:

$$Q_{STP} = 412\ \text{ft}^3/\text{min}$$

$$\bar{Q}_{H_2O} = \frac{Q_{STP}}{(Q_{air}/\bar{Q}_{H_2O})_{\text{theoretical}}} = \frac{412}{13.1} = 31.5\ \text{ft}^3/\text{min}$$

and from Equation III-6 in Appendix C-3:

$$t^* = \frac{105}{31.5} = 3.33\ \text{min (200 sec)}$$

Note that this predicted sinking time is about twice that predicted for the 1967 Chevrolet Impala.

b) <u>Condition 1 (air intake closed)</u>--From the percentage air-leak reduction (29.9 percent) shown in Table 3.17, a figure can be obtained for the leak rate at this condition of:

$$Q_{STP} = (155/221)(412) = 289 \text{ ft}^3/\text{min}$$

From this:

$$\bar{Q}_{H_2O} = \frac{289}{13.1} = 22.0 \text{ ft}^3/\text{min}$$

and:

$$t^* = \frac{105}{22.0} = 4.77 \text{ min (286 sec)}$$

c) <u>Condition 2 (air intake closed, taped around all four doors and windows)</u>--From the percentage of the total air leak (53.4 percent) for this condition shown in Table 3.17 an air leak rate can be obtained of:

$$Q_{STP} = (118/221)(412) = 220 \text{ ft}^3/\text{min}$$

and from this:

$$\bar{Q}_{H_2O} = \frac{220}{13.1} = 16.8 \text{ ft}^3/\text{min}$$

and:

$$t^* = \frac{105}{16.8} = 6.25 \text{ min (375 sec)}$$

It is interesting that simply by having the vehicle in Condition 1 (air intake closed) an increase of 286/200 = 1.43 or a 43 percent increase in t* is predicted.

For the vehicle in Condition 2, with the simple taping scheme used around the doors and windows, an increase of 325/200 = 1.875 or an 87.5 percent increase in t* is predicted.

It is noted that for this vehicle in Condition 2, representing the best condition of water-tight integrity which was tested, a reduction factor of only slightly greater than three (i.e., about 3.2) is required in the residual leak rate to attain a characteristic sinking time, t*, of 20 min. This compares to the reduction factor of about six which is required in the measured residual leak rate for the 1967 Chevrolet Impala (in Condition 6) to achieve a t* of 20 min.

If the ratio of the actual sinking time to the predicted characteristic sinking time of 1.33 determined for the 1967 Chevrolet is characteristic of all vehicles, then we can expect that the actual sinking time of the 1965 Pontiac Tempest would be about 6.25 (1.33) = 8.3 min. This represents a leak rate reduction factor of only 2.4 required to attain the arbitrary sinking time of 20 min.

It is concluded that if the 1965 Pontiac Tempest is more representative of the water-tight integrity of a typical passenger vehicle, that the necessary improvements in the state-of-the-art of compartment sealing do not seem to be of insurmountable magnitude. Perhaps if only moderate changes were made in the seals around the doors and in the firewall even larger leak reductions than required would be effected, giving predicted sinking times of even longer than 20 min.

It is also appropriate to list other related benefits to be gained by a significant reduction in air leaks in the passenger and luggage compartments of the typical, automotive, passenger type vehicle. These are as follows:

1. Elimination of noxious exhaust fumes in the passenger compartment.
2. Elimination of gasoline vapor penetration into the luggage and passenger compartments in post-crash situations thus minimizing compartment fires.
3. Contribution to improved internal air-flow conditions, reducing the overall heat load in the vehicle heating/ air conditioning system.

3.2.3.2 <u>Increase of vehicle sinking times by use of flotation foams</u>: The technique of using plastic foam of a type in which the air spaces are sealed from water penetration is common in the boat industry as a means of preventing the craft from sinking after capsizing, swamping, or sustaining structural damage. This same technique might be applied in the automotive industry.

From the characteristics of the 1967 Chevrolet Impala which was used in the 1970 submergence tests, it is possible to estimate the minimum amount of flotation foam required to enable the vehicle to remain afloat for an indefinite period. In order to make this estimate of the required flotation volume, the expression for t* developed in Appendix C-3 as Equation III-5 can be used:

$$t^* = V_{H_2O}/\bar{Q}_{H_2O} \qquad \text{(III-5)}$$

where V_{H_2O} is the volume of the water taken aboard the vehicle which is just sufficient to cause the vehicle to pass underneath the surface of the water. Defining this water volume in terms of the vehicle weight, W_v, the vehicle structural volume, V_s, and the vehicle internal air volume, V_{ia}, as in Equation III-4:

$$V_{H_2O} = \frac{W_v}{\rho_s} + V_{ia} - \frac{W_v}{\rho_{H_2O}}$$

Inserting the values for these vehicle properties used previously for the 1967 Chevrolet Impala:

$$W_v = 4230 \text{ lbf}$$
$$\rho_s = 780 \text{ lbf/ft}^3$$
$$V_{ia} = 176.1 \text{ ft}^3$$

with $\rho_{H_2O} = 62.4 \text{ lbf/ft}^3$ (for the specific weight of water) we obtain:

$$V_{H_2O} = \frac{4230}{780} + 176.1 - \frac{4230}{62.4} = 113.6 \text{ ft}^3$$

The residual air volume, V_{ra}, remaining in the vehicle at this instant is:

$$V_{ra} = V_{ia} - V_{H_2O} = 176.1 - 113.6 = 62.5 \text{ ft}^3$$

This volume represents the minimum amount of entrapped air (somewhere inside the vehicle structure) which would be necessary to keep the vehicle from sinking for an indefinite period. It is roughly estimated that about one-half of this amount, i.e., about 30 cubic ft, is available in the following locations:

1. Passenger seats, 10 ft^3
2. Engine compartment, 10 ft^3
3. Door compartments, 5 ft^3
4. Miscellaneous locations (under dash, firewall, trunk, frame, etc.) 5 ft^3

It is not readily apparent if other locations are available in this vehicle to make up the additional 32.5 ft^3 of entrapped air which is required to keep the vehicle afloat indefinitely. If the additional assumption is made, consistent with the order of the other assumptions made in this estimate, that the plastic foam is of sufficiently low density and high air-volume content that the weight and volume occupied by the plastic can be neglected, then the following conclusion can be drawn: The 30 ft^3 of residual air space available for a light weight plastic foam is about one-half of the total volume required for the vehicle to float indefinitely. However, it is quite possible that the use of this much flotation foam would result in a marked increase in the actual sinking time of the vehicle due to the smaller amount of vehicle structure below the external water line, i.e., with the vehicle riding higher in the water. This reduction in water leak areas, coupled with the lower water head on the leaks in the vehicle structure under water, would result in a significant reduction in the water leak rate (see Equation II-2 in Appendix C-2). While it is not possible to determine this expected increase in sinking time to a high degree of accuracy, it is certainly apparent that these effects insure a reduction in the leak rate by a factor of two to three with the use of about 30 ft^3 of flotation foam. It is quite possible, then, that by making use of improved vehicle sealing techniques in addition to the use of flotation foam, the sinking time of a typical four-door family sedan could be increased even greater than the arbitrarily selected value of 20 min.

It would also be appropriate to list the related benefits to be gained from the use of flotation foams:

1. Thermal insulation against external fires (if high-temperature foam were utilized).
2. Reduction of heat load by foam insulation and consequent reduction in heater/air conditioning system requirements.
3. Foamed metal (aluminum) which has been proposed to decrease the g-loading in front-end accidents can contribute significantly to the required flotation foam in this location.
4. Foamed metal (aluminum) which has been proposed to be used in doors to reduce g-loadings from side impact can also contribute to the vehicle flotation characteristics.
5. Consistent with industry design trends, foam used in floor pan, fire wall and the luggage compartment can contribute significantly to noise reduction in the passenger compartment.

3.2.6.3 Status of related studies:

1. In the appendix of the previous reported effort (1) an English translation from the Netherlands language was presented of a related study. This study was in the form of a progress report of an extensive submergence study begun in 1968 in the Netherlands. It has been ascertained that the final report is now available (in the Netherlands language) describing these studies in more detail. Also, a documented film showing the experimental phase of these studies is available in English. It has been learned that no continuance of these studies is being conducted at the present time due to lack of financial support.
2. In the early phases of the studies conducted during this contractual period, contact was made with personnel of the United States Army Tank-Automotive Command

in Warren, Michigan, concerning the availability of U.S.army vehicle flotation studies pertinent to the present effort. The chief scientist of the command, Dr. E. Petrick, was contacted initially and was informed of the submergence aspects of the present DOT studies. At his suggestion, correspondence was initiated with T. F. Czako, Vehicle Locomotion Projects, at the same command. Five reports containing the most significant related studies were subsequently obtained covering both in-house and out-of-house studies. These reports cover several interesting vehicle flotation studies and would be available as a technology state-of-the-art input for any contemplated passenger vehicle flotation improvement studies to be conducted in the future.

These reports are listed for reference here as follows:

1. "Feasibility Test of the GACA Flotation Kit, M3," GERA-851 November 14, 1963, Goodyear Aerospace Corporation, Arizona Division, Citchfield Park, Arizona.
2. "1/4 Ton Truck Flotation Studies," prepared by F. R. Winson, April 1965, U.S. Army Tank Automotive Center Research and Engineering Directorate, Warren, Michigan.
3. "Studies of Off-Road Vehicles in the Riverine Environment," Report 1382, Volume 1, Performance Afloat, October, 1968, I. R. Ehrlich, I. O. Kamm and G. Worden, Davidson Laboratory, Stevens Institute of Technology, Castle Point Station, Hoboken, N.J.
4. "Water Performance Tests of the Wheel Pump Installed on a 1/4-Ton Truck Floater/Swimmer," Report SIT-DL-70-1450, March 1970, D. A. Sloss, Davidson Laboratory, Stevens Institute of Technology, Castle Point Station, Hoboken, N.J.

5. "Doughnut Equipped 1/4-Ton Flotation Test (Phase II), February 1968, F. D. Palazolo, Systems Formulation Branch, System Concept Division, Development and Engineering Directorate, U.S. Army Tank-Automotive Command, Warren, Michigan.

3.2.7 General Conclusions and Recommendations

From the results and conclusions drawn regarding the detailed studies presented in the previous sections, general conclusions will be drawn and recommendations will be made for additional studies, both experimental and theoretical, in the areas that would seem most fruitful.

The following conclusions can be drawn:

1. From the literature survey done in the area of water-entry processes, it appears that the more sophisticated computer program allowing the treatment of the unsteady flow, "virtual mass" effect at initial enery, followed by the quasi-steady remainder of the entry process, allows a more realistic treatment of the vehicle water-entry dynamics. However, it remains to be determined from full scale tests whether air-entrainment and cavitation, which are peculiar to automotive vehicle entry, compared to the case of the more streamlined shapes which have been studied in the past, have been approximated by the cavity-drag and spherical leading edge entry assumptions which have been incorporated in the more sophisticated computer program.
2. It appears that the dry-land leak-simulation scheme which allows the prediction of a vehicle's characteristic sinking time, provides a very convenient, rapid and inexpensive means for the determination of the relative sinking characteristics of various vehicles. It is believed that the relatively close agreement of the theoretically predicted water leak-rates and

sinking times (within 33 percent of the water leak-rates and sinking times measured in the March 1970 submergence tests) demonstrates the validity of the experimental techniques employed and the assumptions involved in the analysis.

3. A technique has been developed for the measurements of the vehicle air-flotation volume using the gas-concentration method employing the Kitagawa gas sampler method involving batch-type sampling. The results were checked to a reasonable accuracy (to within 7 percent) of the more accurate method employing the Beckman O_2-Analyzer which involved continuous sampling. These methods also showed reasonable agreements (to within 15 percent) compared with the more direct but time consuming method using the positive displacement balloon technique. It is noted that this latter positive displacement method provides a definite lower bound to the magnitude of the vehicle's air-flotation volume. It is suggested that the gas-concentration method should be investigated by the industry for the rapid, inexpensive determination of vehicle compartment volumes, the reporting of which has been discontinued reportedly due to the relative inaccuracy of the data published in the past.

Based upon the above conclusions, the following recommendations are advanced:

1. It is recommended that a few carefully documented vehicle water-entry experiments be conducted in which different types of full-scale salvage (damaged) vehicles are tested. Typical, controlled water-entry velocities and entry angles should be employed as a check on the validity of the predictive computerized model which has been developed.

2. It is recommended that full-scale, unmanned experimental submergence studies to determine leak-rates and sinking times be conducted using salvage vehicles with the passenger and trunk compartments fully intact. Vehicles of the same make and model as the four vehicles which have been tested in the dry-land, leak-simulation tests (i.e., the 1967 Chevrolet Impala, 1965 Pontiac Tempest, 1971 Ford Pinto and the 1970 American Hornet) should be the first group of vehicles tested. This selection will provide the most useful data, since extensive air leak flow-rate data have been obtained for these vehicles. In addition, dry-land, air leak flow-rate tests should be conducted using these salvage vehicles before and after the water-submergence studies for comparison purposes.

   These studies should allow a much greater degree of confidence in the predicted accuracy of the correlation between the dry-land leak simulation tests and the data deduced from actual water submergence studies.

3. It is recommended that after the studies made in 2 above have demonstrated the degree of correlation for the types of vehicles tested, that other types of salvage vehicles be tested representing a more complete spectrum of vehicle types. Again, the dry-land air-leak simulation tests should be conducted before and after the water submergence tests to determine the effect of irreversible vehicular damage on the degree of correlation between these tests.

3.3 BUS ESCAPE STUDIES

The accident literature available on the subject of bus escape problems in the post-crash environment was reviewed as a part of Contract No. FH-11-7303 which was completed in December, 1970 (1). Inadequacies in the available accident data were pointed out in the report covering that contract, and these problems continue to exist. However, progress is being made in gathering meaningful data, primarily through the investigations performed by the National Transportation Safety Board and the In-depth Accident Investigation Teams sponsored by the National Highway Traffic Safety Administration.

Unfortunately, these added efforts to collect the necessary data have not yet produced sufficient accident data for the present purpose. Consequently, data obtained by the National Safety Council (6), (7), which are open to question, will have to be used here. Their estimate of bus passenger deaths and death rates are shown in Table 3.21. It can be seen that a downward trend in passenger mileage death rates has been posted for the last two years, even though the current death rates for 1969 and 1970 are estimated as being higher than for several of the years during the 1960's.

The National Safety Council in Accident Facts has continued to estimate that approximately 25 school bus passengers are killed each year, starting with the year 1967 (6), (7). These are passengers killed while riding a bus involved in an accident, rather than as pedestrians entering or leaving the school bus. No data are available to indicate whether any of these estimated fatalities are the result of escape and rescue problems.

TABLE 3.21

BUS PASSENGER DEATHS AND DEATH RATES, 1950-1970

Year	Bus Fatalities	Death Rate per 100 Million Passenger Miles
1950	100	0.18
1951	130	0.24
1952	100	0.21
1953	70	0.18
1954	60	0.11
1955	100	0.18
1956	80	0.16
1957	100	0.19
1958	90	0.17
1959	110	0.21
1960	70	0.13
1961	100	0.19
1962	60	0.11
1963	150	0.26
1964	90	0.15
1965	100	0.16
1966	150	0.23
1967	120	0.18
1968	160	0.24
1969	150	0.22
1970	130	0.19

3.3.1 Literature Review

The report for Contract FH-11-7303 (1) included a review of the literature covering previous investigations of bus safety. This review will focus on the relevant literature which has become available since early 1970, which was the terminal point of the previous review.

The Bureau of Motor Carrier Safety has reported that a total of 8 people were killed in 1969 while riding buses of Class 1 motor carriers, which are defined as interstate motor carriers of passengers having annual operating revenues of $1,000,000 or more (8). This same publication indicates that 80 bus drivers and 1,520 bus passengers were injured during the year 1969.

For the year 1970, the Bureau of Motor Carrier Safety (9) indicates that 2 bus drivers and 11 passengers became fatalities in accidents involving Class 1 motor carriers, while 17 drivers and 438 passengers were injured. In a further breakdown of the driver and passenger fatalities, it is indicated that one bus driver was ejected through the bus windshield, and 9 passengers were ejected through side windows.

In considering the Bureau of Motor Carrier Safety statistics for these years it must be noted that they are not intended to be all-inclusive, but rather they represent a selection of accidents for analysis to point out certain safety problems. Because the incidence of passenger fatalities due to ejection has been observed over a period of years, present regulatory provisions require that side windows be more securely fastened.

The National Highway Safety Bureau has recently taken final action to establish new standards for bus safety as listed below:

1. Pupil Transportation Safety--Highway Safety Program Standard No. 17--National Highway Traffic Safety Administration
2. Bus Window Retention and Release--Federal Motor Vehicle Safety Standards, Part 571, National Highway Traffic Safety Administration

The first standard entitled "Pupil Transportation Safety" is

> . . . designed to improve state programs for transporting pupils safely in urban and rural areas by setting requirements for proper and safe equipment; maintenance of equipment; selection, training, and supervision of drivers and maintenance personnel; and administrative provisions in the field of pupil transportation.

The provisions of this regulation that are of interest in the area of escape worthiness are the requirements that each pupil transported on a bus receive instruction and participate at least twice each year in emergency evacuation drills, and that a regular program of bus maintenance be established, including operation of emergency exits.

The second standard entitled "Bus Window Retention and Release" has the following scope:

> This standard establishes requirements for the retention of windows other than windshields in buses, and establishes operating forces, opening dimensions, and markings for push-out bus windows and other emergency exits.

This standard encompasses many aspects of escape worthiness and will be discussed further in relation to the experimental and analytical evaluations of bus escape worthiness which follow.

The Vehicle Equipment Safety Commission has issued a specification entitled Minimum Requirements for School Bus Construction and Equipment which has some provisions concerned with emergency exits which will be discussed later (10).

The National Conference on School Transportation has also published a document entitled Minimum Standards for School Buses (11). This document supersedes the 1964 Revised Edition of the same publication. A discussion of applicable standards from this publication as compared to other publications follows in a later section.

3.3.2 Experimental Design and Procedure

The bus escape studies conducted under Contract FH-11-7303 (1) allowed an experimental methodology to be developed for studying bus escape worthiness. This methodology of necessity was based on a subset of all the possible experimental variables which can affect escape worthiness. The resources available and the safety of experimental subjects dictated that certain variables be omitted from these studies, although it is recognized that they may affect escape worthiness. These variables are mentioned in the appropriate subsections which follow. Given that a set of variables were chosen for study, then the appropriate equipment necessary for establishing the experimental conditions and obtaining data was developed and utilized as described in the following sections.

3.3.2.1 Independent variables: The primary independent variables are related to the design features of the bus, the personal characteristics of the subjects acting as passengers and the physical environment in which the tests are to be conducted.

1. Vehicle--The principal variable related to escape is quite obviously the quality of the exits, such as the number, size, location, marking or identification and the force required for opening. Variables such as seat design, type of floor covering used, height of exit above ground level, provision of emergency

lighting, provision for axes or other escape tools, the final position of the bus, the crash damage sustained, and the presence of fire can also have an effect on escape.

2. Passengers--Two sets of variables can be distinguished when the effects of passengers on escape are analyzed. One set of variables includes things which are deterministic, such as age, sex, anthropometric dimensions, weight and total number of passengers. The other set of variables includes those which are probabilistic in their effect on escape time, such as panic, injuries sustained, and previous escape drills. Other factors such as the arrangement of passengers in a bus may also have an effect on escape time.
3. Environment--The variables within the environment that can influence post-crash escape are darkness, obstructions in escape routes, submergence in water, extravehicular fires and availability of emergency aid.

During the course of these escape tests observations were made relating to the following independent variables, either directly or indirectly:

1. Number of exits available
2. Size of exits
3. Location of exits
4. Operating method and strength required for opening exits
5. Access of passengers to exits
6. Height of exit above ground level
7. Attitude of bus, whether upright or on the side
8. Composition of passenger load
9. Environmental conditions of daylight and darkness

The number and type of exits available and conditions of daylight and darkness were investigated at two or more levels for each variable.

Studies of bus escape worthiness performed under Contract No. FH-11-7303 emphasized school bus escape worthiness. While both school buses and intercity buses were studied under this contract, FH-11-7512, more emphasis has been given to intercity bus escape problems to achieve a total balance of information in this area.

The studies of escape worthiness and bus window retention performed under Contract No. FH-11-7303 (1) demonstrated that human strength data were needed to properly evaluate and design bus emergency exit latching and retention mechanisms. An initial study to obtain such data was performed as a part of this contract, although the funds available did not permit the extensive testing which would be useful in adequately defining human strength capabilities.

3.3.2.2 Dependent variables: Included in this group are time to escape, passenger behavior, and injury.

1. Time to effect an escape is of prime importance when fire is present; where there are approaching trains or other vehicles and the bus is stalled; when the bus goes into water; and when medical aid is urgently needed. Escape times were measured using both motion picture film with an accurate time base and with special timers.
2. Behavior in escaping was obtained solely by visual methods employing multiple motion picture coverage of the escape process and direct observation.
3. Injury occurrence while escaping and the potential for injury were observed and recorded.

3.3.2.3 Subjects: The University of Oklahoma College of Education operates a laboratory school with twelve grades. Subjects were obtained from this population for use in the school bus escape trials. Permission to serve as subjects was obtained from the parents of all children.

Surveys of passenger load composition and seating arrangement were conducted in the local area with the following results:

1. School buses can vary greatly in the passenger load composition, depending upon the school busing arrangements. Some buses transport loads having the entire twelve grades represented. Others segregate loads according to grade school, junior high and high school.
2. For school buses in the local area transporting a mixed load of all twelve grades, the seating arrangement was found to be:
    a. Smaller children preferred the back of the bus.
    b. Larger children preferred the middle of the bus.
    c. The remainder sat closer to the front.

Using this information as a guide, subjects were selected to provide equal representation from all twelve grades and were seated on the bus in accordance with the preferences found in the survey. Approximately equal representation of boys and girls was obtained although this grouping varied from test to test due to substitutions for illness and availability of subjects in each grade.

No control of anthropometric dimensions was exercised in selecting subjects for the school bus tests, but subsequent checks indicated none of the subjects were at the population extremes of size. From 66 to 68 children from all twelve grades comprised the subject groups for the various school bus escape tests. Clothing worn by the children did not include any heavy coats, with most wearing a sweater or light jacket, although some did not wear a coat.

The subjects participating in the intercity bus escape tests were selected on the basis of a survey taken of passengers who ride buses. This survey was taken by direct observation of passenger loads in the Oklahoma City bus station. The results obtained were later confirmed by contact with public relations personnel of the Greyhound Bus Company. Using this information, a subject population was assembled as shown in Table 3.22 to participate in the intercity bus escape tests. A comparison of the subject population actually assembled versus the observed data is shown in Table 3.23.

An examination of Table 3.23 shows that the principal difference in the experimental subject group and the observed passenger characteristics is the absence of females over 60 years of age in the experimental group. This difference can be attributed to a decision by the experimenters that the risk of injury was too great for females in this age group to participate. More commentary on this aspect will be given later in the Results, Section 3.3.3. While other differences in the two populations can be observed, it is believed that they would not significantly affect the results obtained. Thus, it would be expected that the escape times obtained for the different conditions are better than could be obtained in actuality because of the subject differences noted.

All of the subjects who participated in the intercity bus escape tests received payment for participating.

The clothing worn by the subjects for the intercity bus escape tests did not include any large, heavy coats which would restrict movement. Typical attire included a shirt or blouse and pants with a sweater or jacket. All females except one wore pants, rather than a skirt or dress.

3.3.2.4 Equipment: Escape tests were conducted from a 72 passenger school bus and a GMC intercity bus, Model PD4104. Other supporting equipment included movie and still photographic lighting equipment, cameras, goggles

TABLE 3.22

SUBJECT POPULATION DATA FOR INTERCITY BUS ESCAPE TESTS

Subject Number	Age (Years)	Height (Inches)	Weight (Pounds)	Sex
1	4	31	35	Male
2	6	48	48	Male
3	13	61	120	Male
4	14	63	97	Male
5	17	72	153	Male
6	17	68	110	Male
7	18	64	110	Female
8	18	71	138	Male
9	19	69	140	Male
10	21	73	180	Male
11	22	72	150	Male
12	23	70	165	Male
13	24	74	210	Male
14	24	75	200	Male
15	26	70	165	Male
16	28	72	170	Male
17	28	63	108	Female
18	29	66	134	Female
19	33	65	112	Female
20	34	67	135	Female
21	35	72	160	Male
22	35	71	220	Male
23	38	69	168	Male
24	40	67	120	Female
25	41	62	115	Female
26	43	70	180	Male
27	43	66	145	Female
28	44	76	250	Male
29	44	63	110	Female
30	46	65	141	Female
31	47	63	160	Female

TABLE 3.22 (Continued)

Subject Number	Age (Years)	Height (Inches)	Weight (Pounds)	Sex
32	49	68	168	Male
33	50	71	210	Male
34	51	66	160	Female
35	53	65	155	Female
36	55	71	185	Male
37	56	63	135	Female
38	56	66	156	Male

TABLE 3.23

COMPARISON OF INTERCITY BUS ESCAPE TEST SUBJECTS WITH OBSERVED DISTRIBUTION OF BUS PASSENGERS BY AGES

Age Range	Percentage in Escape Tests		Percentage Observed Riding Buses	
	Male	Female	Male	Female
0 - 5	2.6	0.0	1.5	2.3
5 - 18	15.8	2.6	9.1	6.4
18 - 30	21.1	5.3	25.8	16.2
30 - 45	13.1	15.8	7.6	5.7
45 - 60	10.5	13.2	6.4	5.7
over 60	0.0	0.0	1.9	11.4
Total (percentage)	63.1	36.9	52.3	47.7
Total (people)	24	14	138	126

for subjects, a siren, timers, first-aid kits, mattresses, and anthropometric measuring equipment.

1. School Bus--A list of the pertinent specifications for the bus utilized in the escape trials is given below:

CONDITION:	Used, obtained by rental from local dealer.
CHASSIS:	GMC Truck #26573
BODY:	Manufactured by Ward Body Works, Conway, Arkansas, Model M 3410
STATED PASSENGER CAPACITY:	72
WINDOWS:	Split-sash, fixed windows with an opening of 24 in wide by 12 in high when lowered were installed as side windows. A total of 12 windows were installed on the right side of the bus and 11 on the left side. Distance from the lowered window sill to the ground was 87 in. A rear window was available as an emergency exit on this type of bus. Its dimensions were 55 in wide by 24 in high, with a distance of 72 in from the window sill to the ground. Figure 3.44 shows the rear window opened. Figure 3.45 shows the type of latch used at both corners of the reat emergency exit window. Opening of the rear emergency exit door interfered with the use of the adjacent window as an escape route because the window area is covered by the opened door.

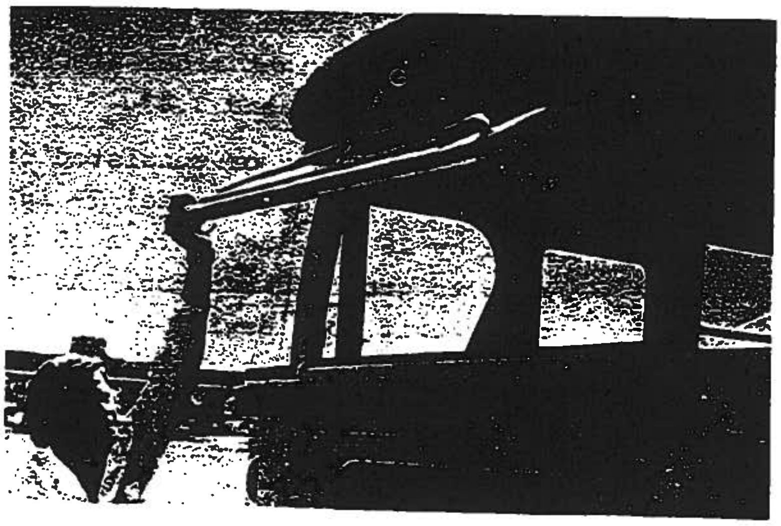

Figure 3.44. View of opened rear escape window for 72-passenger school bus used for tests.

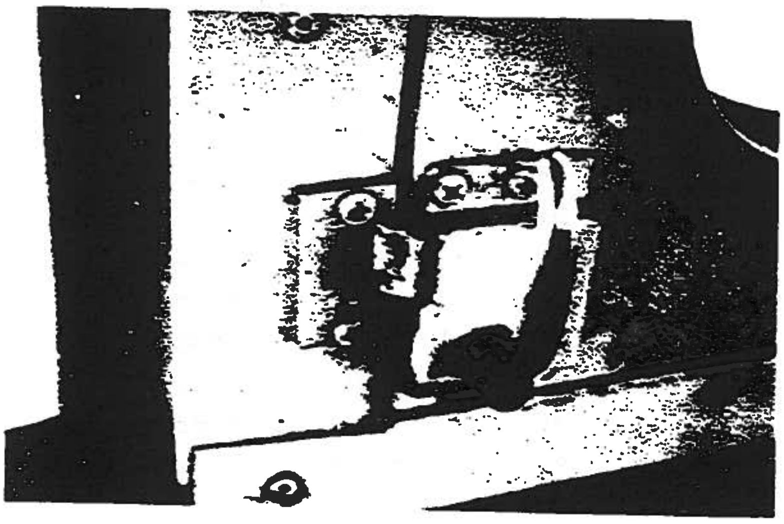

Figure 3.45. View of latch used at each side of rear escape window of 72-passenger school bus.

Overall views of the bus from the left and right sides are shown in Figures 3.46 and 3.47.

DOORS: Front entrance door consisted of a jackknife pressed panel 77 in high by 26 in wide, with a 15 in step to ground dimension. An emergency exit door having a width of 24 in and a height of 58 in was installed in the left rear side of the bus. Distance from door sill to ground was 39 in.

The rear emergency exit door can be seen in Figure 3.46 and the front door can be seen in Figure 3.47. Figure 3.48 shows the rear emergency exit door with the operating instruction. Figure 3.49 shows the type of operating lever for opening the rear emergency exit door.

SEATS: Eleven rows of seats were installed on either side of the bus, with additional seating space across the entire rear of the bus under the emergency exit window. A view showing the seating in the interior of the bus is shown in Figure 3.50.

The bus was rented from an Oklahoma City firm and was currently used for transporting pupils. It conformed to the Minimum Standards for School Buses set forth in the 1964 Revised Edition (12).

2. GMC intercity bus--Bus specifications pertinent to the escape tests are as follows:

Figure 3.46. Left side view of 72 passenger school bus used for escape tests.

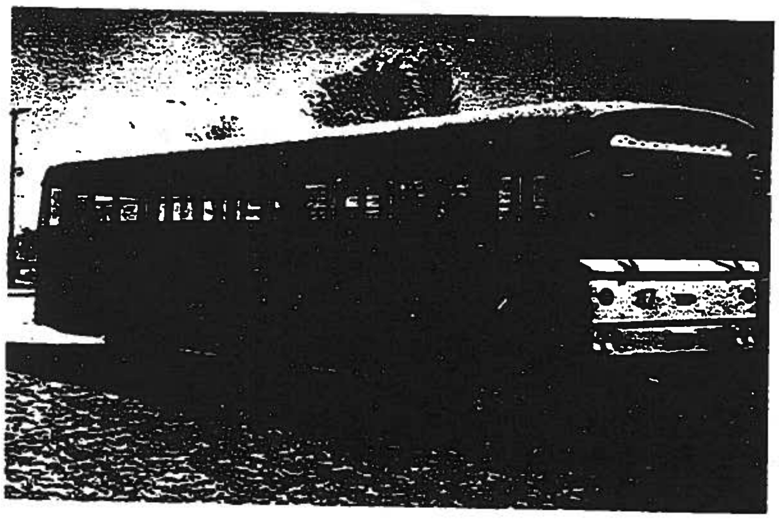

Figure 3.47. Right side view of 72-passenger school bus used for escape tests.

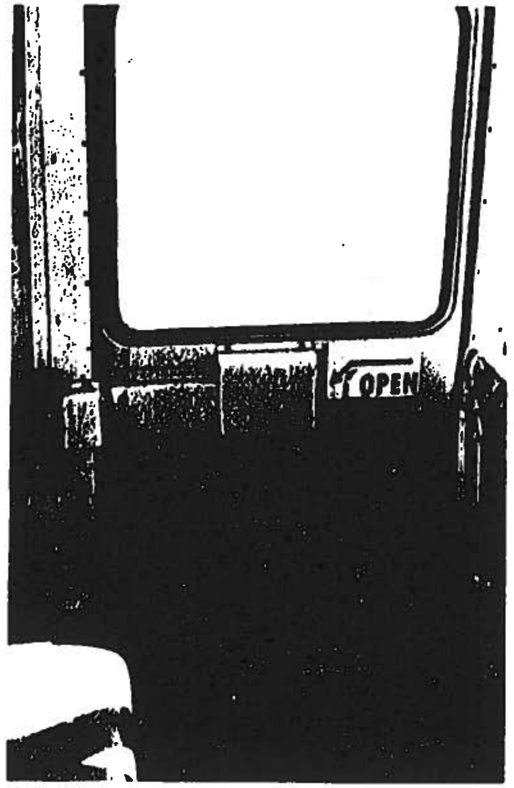

Figure 3.48. Overall view of left rear emergency escape door for 72-passenger school bus used for escape tests.

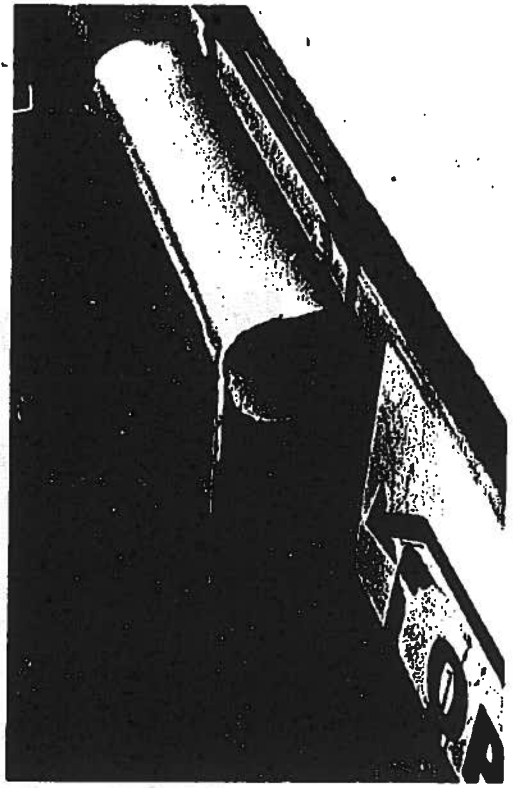

Figure 3.49. View of left rear emergency door latch operative mechanism for 72-passenger school bus.

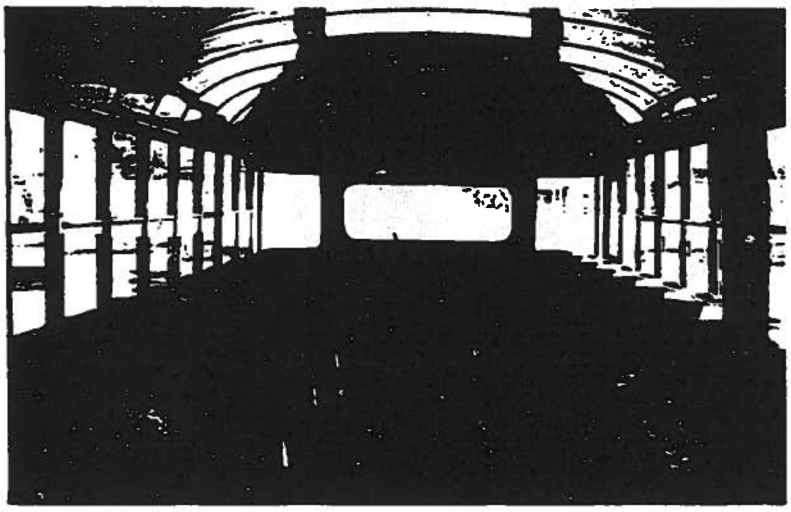

Figure 3.50. Interior view of 72-passenger school bus used for escape tests.

CONDITION:	Used, in normal service, chartered for conducting the experimental study.
MANUFACTURER:	General Motors Coach Division
TYPE:	Model PD4104
CAPACITY:	39 passengers (lavatory equipped)
EMERGENCY EXITS:	Seven push-out windows, 4 on the right side and 3 on the left side of bus. One emergency exit door 25 7/8 in wide by 50 in high on left rear of bus. Windows are opened by lifting push-bar and pushing against secondary friction latch. Height of window sill above ground level is 6 ft. Height of emergency exit door sill is at floor level, 3 ft, 9 in above ground level.
SEATS:	Ten rows of 2 seats on each side of aisle, one seat in center of bus at rear end of aisle. Further details of the bus and escape exits are covered in the discussion of the escape tests.

3. <u>Supporting equipment</u>--Two 16 mm motion picture cameras were used to film the series of escape trials for the school bus. These cameras were also used later to film the intercity bus escape trials.

    Previous research conducted under Contract FH-11-7303 (1) had demonstrated that a specially constructed goggle provided a satisfactory simulation of darkened conditions for an escape trial, so this method was again used for the escape tests. The goggles were specially fabricated by spraying black paint over a dark plastic material until very little light was transmitted.

The amount of available light transmitted was approximately five percent. The uneven pattern of spray paint and low light transmission provided both disorientation and very poor vision. A secure fit for all size heads was obtained by using an elastic band and sponge padding around the eyes.

A loud siren was used to signal the start of each test; it remained on throughout the escape process.

Two large timers were strategically placed to provide a check on the time base of the movie film taken. The timers had a 10 in face; one revolution of the sweep hand occurred in six seconds (one-tenth of a minute). The siren and timers were synchronized.

A medical doctor or a registered nurse supplied with a complete first-aid kit was available to treat injuries. Fortunately, because efforts were made to reduce the hazard in escaping, no major injuries occurred. It is unlikely that passengers in an actual escape will be so fortunate.

Used mattresses were placed along both sides and the rear of the buses to provide a landing cushion for the subjects as they jumped from the bus as will be seen in subsequent photographs in the next section.

3.3.2.5 Escape tests: The methodology to be used for performing escape tests was developed under contract FH-11-7303 and that background will not be repeated here (1). Escape tests for the school bus will be described first, and then the escape tests for the intercity bus.

A series of escape trials were designed to investigate daylight and darkened conditions. These trials were conducted with the group of subjects previously described for the conditions shown below:

Trial 1: Subjects wore goggles to simulate the condition of darkness. All side windows, the rear emergency exit window, and the rear emergency exit door in the side of the bus were available for escape.

Trial 2: The same conditions were used as for Trial 1, except that the rear emergency exit door was also blocked in addition to the front door.

Trial 3: Subjects wore no goggles and escaped through all windows and doors.

Trial 4: This trial was a replicate of Trial 1.

Trial 5: Subjects wore goggles and escaped through all exits.

The subjects were simply informed that they would participate in the school bus escape tests after permission was obtained from their parents. However, they were not provided any other information about the details of the escape prior to entering the bus. Subjects were assembled as a group prior to each series of tests to check for substitutions and to instruct them in the seating arrangement to be followed in the bus.

Since the school bus was stationary throughout the tests, it was feasible to position and check the camera angles in advance. The bus windows were all closed in their normal raised positions and the emergency exits were checked for closure. After the mattresses for breaking the fall were checked for proper placement, the subjects were led from an adjacent building to the bus. The entrance door was then closed. The bus engine was then started and was kept running throughout the trial. A research assistant acting as the bus driver then gave verbal instructions regarding the siren which would signal the escape to begin and the use of goggles on each trial.

No further instructions were given about which escape exits to use for any trial, since the emergency exits which were not to be used had been taped shut to prevent their use. The bus driver prevented any escape through the front door by holding the release handle.

Upon a previously arranged signal from the bus driver, the cameras were started, and five seconds later the siren and timers were started. The start signal was randomly timed within a two or three minute interval to avoid anticipation of the start by the subjects. Two cameras covered the bus, one on each side of the bus. Filming continued until the bus was evacuated.

After completing each trial the subjects entered the school bus again and received instructions for the next trial. The bus and equipment were made ready and the escape trials continued until all were completed.

A small change in the number of subjects participating in each trial was necessary because some small children did not participate in the first two trials, and other children were slightly injured and did not participate in subsequent trials. This change in subject count is discussed in the Results.

Selected scenes from the escape trials are shown in Figures 3.51 and 3.52.

The intercity bus escape trials were conducted inside a large building used as a research facility, rather than outside as was the case for the school bus trials. This facility allowed the intercity bus previously described to be prepared for the escape trials prior to subjects arriving at the site. Two motion picture cameras were used to film the escape, one on either side of the bus. A light and siren were used to signal the start of each trial. The large timer described earlier was

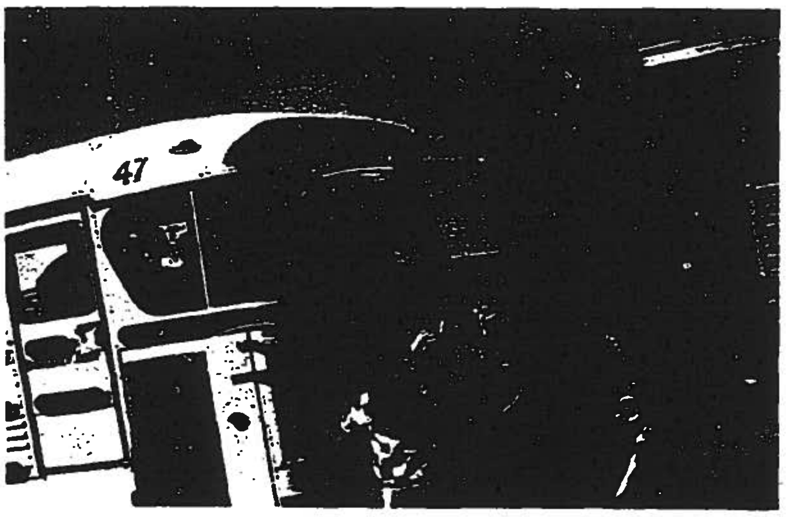

Figure 3.51. View of subjects escaping from the rear window of 72-passenger school bus.

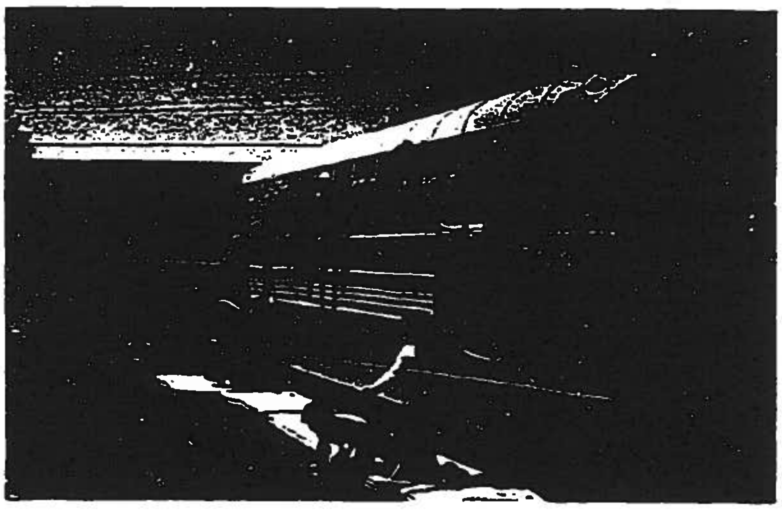

Figure 3.52. View of subjects escaping from the left rear door and windows of 72-passenger school bus.

placed in view of one of the cameras to obtain a check on the time base of the movie camera. Mattresses were placed under all exits to help protect subjects against injury when escaping. Cameramen were given a signal to start the movie cameras five to ten seconds before the signal to begin the escape trial.

As the subjects arrived at the research facility they were taken to a waiting area where researchers recorded personal and anthropometric data and fitted them with goggles. They were not allowed to enter the vicinity of the PD4104 bus.

After all data had been obtained and all preparations checked, the subjects were led to the bus in a group and they were allowed to choose any seat they wished.

The researcher acting as the bus driver then explained the importance of the research and impressed upon the subjects the need to escape as rapidly as possible. No instructions were given about how to operate any window or door when escaping from the bus. The researcher acting as the bus driver gave instructions about which exits were to be used for escape each time and whether goggles were to be used or not. Each of the following escape trials were then conducted in sequence until all were completed:

Trial 1: Subjects wore goggles to simulate darkened conditions. Only windows were available as escape routes.

Trial 2: Subjects did not wear goggles and escaped through both windows and the emergency exit door in the left, rear side of the bus.

Trial 3: Subjects wore goggles and escaped under the same conditions as for Trial 2.

Trial 4: Subjects did not wear goggles and escaped through windows, the front door and rear emergency exit door.

The lavatory retrofitted on this bus partially blocked the rearmost pushout window on the right side of the bus. It was possible to operate the pushbar release mechanism on this window, but pushing the window open against the remaining frictional resistance proved difficult when pushing from only one end of the window. Figure 3.53 shows subjects escaping through the three large windows on the right side of the bus. Figure 3.54 shows subjects escaping from the left side of the bus. Note that some males are voluntarily holding windows open for others to escape. Without such spontaneous assistance, the escape times would have been lengthened substantially.

Qualified medical personnel were in attendance for all escape trials and treated the injuries to fingers resulting from windows swinging back shut on subjects after the preceding subject had escaped. The mattresses employed as landing pads helped to prevent any serious injuries to subjects as they jumped from the windows and doors to the mattresses.

All subjects were given a debriefing which was tape recorded for later analysis to explore their problems in escaping and suggestions for further consideration in this area.

3.3.3 Results

The motion picture records of the escape tests were analyzed to evaluate the time to escape and problems in escaping for each type of bus. In addition, the tape recording of the subject debriefing performed after the

Figure 3.53. View of subjects escaping from right side of intercity bus, General Motors Model PD4104.

Figure 3.54. View of subjects escaping from left side windows of intercity bus, General Motors Model PD4104.

intercity bus test provided some insights into the problems of escape. Some of the data, such as that for escape time, can be readily quantified, while other information such as the descriptions of escape problems and possible hazards in escaping does not lend itself readily to quantification. The sections which follow present both types of information as clearly as possible, even though it is realized that some of the qualitative information can only be appreciated fully upon review of the motion picture records which have been transmitted to NHTSA.

<u>3.3.3.1 School bus escape trials</u>: Time data for the escape trials are presented in Table 3.24.

A number of observations concerning these data are possible:

1. Students without previous exposure to the type of latching system used on the rear window could not open it on the first series of trials. Figure 3.49, which was presented in Section 3.3.2.4, shows the type of lever-operated latch used on each lower corner of the rear escape window. The movie film of the escape indicates that the confusion present in the bus, plus lack of instructions on how to open the window, prevented both latches from being operated simultaneously to open the window. This same problem occurred again on Trial 4, when only four students escaped through the rear window, even though it had been operated successfully on Trial 3. It seems clear that any latching system requiring such coordinated action to open will prove unsatisfactory in a panic escape situation.
2. The effects of practice under conditions of darkness did not improve the escape time, as measured by comparison of Trial 1 with Trial 4, since Trial 4 was a

TABLE 3.24

RESULTS OF SCHOOL BUS ESCAPE TRIALS

Trial Number	Number Subjects Escaping	Number Children Escaping from Each Exit					Total Escape Time (Seconds)
		Rear Door	Left Windows	Right Windows	Rear Window	Front Door	
1	68	35	12	21		*	53
2	66**	*	21	16	29	*	86
3	68	18	9	15	8	18	31
4	68	34	16	14	4	*	57
5	68	16	8	14	10	20	30

*Exit blocked for this trial.

**Two subjects injured on previous trial did not participate.

replicate of Trial 1. This result demonstrates the need for drill in escaping on a regular basis, with some children trained to coordinate the escape procedure, rather than having an undisciplined escape as occurred during the trials. It was noted that the principal reason for the longer escape time for Trial 4 was a jamming of subjects in the rear of the bus while some students were trying to open the rear window.

3. The effects of wearing goggles to simulate darkness conditions is not evident when comparing the time for Trial 3 with the time for Trial 5.
4. The use of door exits is superior to use of window exits, as will be seen in the analysis which follows.

In order to compare the effectiveness of each type of exit and to determine the extent each type of exit was utilized in an escape, the data presented in Tables 3.25 through 3.29 was developed for each trial as shown in the following pages.

It is evident from observing each table that all escape exits were not utilized fully. This can be attributed to two factors: the confusion existing in a bus as students attempted to find a clear escape route, and the fact that many elementary age children would not attempt to escape through a window 87 in from the ground.

The superiority of a door escape exit is demonstrated in all the escape trials as compared to the side and rear window exits. The escape times for the rear door exit are remarkably uniform for all trials, and also agree with the comparable value of 1.5 sec obtained during the school bus escape trials conducted as a pilot study under Contract FH-11-7303 (1).

Escape from the split-sash type of window, even though it was 12 in high by 24 in wide, was relatively

TABLE 3.25

TRIAL NUMBER 1
ANALYSIS OF OPENING TIME AND USE OF ESCAPE ROUTES

Exit Type*	Time to Open (Seconds)	Time of Last Escape (Seconds)	Number of Escapes	Time per Person Escaping from Exit (Seconds)	
				Including Opening Time	Excluding Opening Time
RW1	5.5	22.2	2	11.1	8.4
RW2	5.9	43.5	3	14.5	12.5
RW3	13.7	26.5	1	26.5	12.8
RW4	4.6	15.6	2	7.8	5.5
RW5	6.0	15.9	1	15.9	9.9
RW6	5.8	26.3	2	13.2	10.3
RW7	3.6	39.0	3	13.0	11.8
RW8	5.0	31.9	3	10.6	9.0
RW9	6.0	36.8	3	12.3	10.3
RW10	5.2	42.0	1	42.0	36.8
LW1	3.2	32.4	3	10.8	9.7
LW2	5.0	30.0	2	15.0	12.5
LW3	2.8	27.7	2	9.4	12.5
LW5	2.7	33.5	2	16.7	15.4
LW6	1.8	53.1	3	17.7	17.1
RD	2.7	52.3	35	1.5	1.4

*RW = Right Side Window
LW = Left Side Window
FD = Front Door
REW = Rear Escape Window
RD = Rear Escape Door

TABLE 3.26

TRIAL NUMBER 2
ANALYSIS OF OPENING TIME AND USE OF ESCAPE ROUTES

Exit Type*	Time to Open (Seconds)	Time of Last Escape (Seconds)	Number of Escapes	Time per Person Escaping from Exit (Seconds)	
				Including Opening Time	Excluding Opening Time
RW1	7.8	24.2	1	24.2	16.4
RW2	7.9	35.0	2	17.5	13.6
RW4	4.9	20.9	2	10.5	8.0
RW5	4.4	25.0	2	12.5	10.3
RW6	4.4	44.5	2	22.3	20.0
RW7	4.2	28.3	2	14.2	12.1
RW8	6.3	31.3	3	10.4	8.3
RW9	5.2	36.5	2	18.3	15.7
LW1	4.5	34.5	2	17.3	15.0
LW2	4.7	31.3	2	15.6	13.3
LW3	4.6	21.9	2	10.9	8.7
LW4	4.4	26.8	2	13.4	11.2
LW5	6.6	34.0	2	17.0	13.7
LW6	4.9	39.0	2	19.5	17.1
LW7	6.5	29.5	2	14.8	11.5
LW8	4.0	21.0	3	7.0	5.7
LW9	4.3	26.0	2	13.0	10.9
LW10	7.0	27.8	2	13.9	10.4
REW	4.8	85.9	29	3.0	2.8

*RW = Right Side Window
LW = Left Side Window
FD = Front Door
REW = Rear Escape Window
RD = Rear Escape Door

TABLE 3.27

TRIAL NUMBER 3
ANALYSIS OF OPENING TIME AND USE OF ESCAPE ROUTES

Exit Type*	Time to Open (Seconds)	Time of Last Escape (Seconds)	Number of Escapes	Time per Person Escaping from Exit (Seconds)	
				Including Opening Time	Excluding Opening Time
RW1	9.2	23.9	2	11.9	7.4
RW2	1.3	27.6	2	13.8	13.2
RW3	2.2	23.0	2	11.5	10.4
RW5	4.8	18.3	1	18.3	13.5
RW6	1.4	22.9	3	7.6	7.2
RW7	1.4	15.7	1	15.7	14.3
RW8	1.2	5.8	1	5.8	4.6
RW9	2.0	21.0	2	10.5	9.5
RW10	2.3	16.3	1	16.3	14.0
LW1	2.7	24.6	3	8.2	7.3
LW5	2.0	13.9	2	7.0	6.0
LW6	3.2	14.3	1	14.3	11.1
LW9	2.0	31.1	2	15.6	14.6
LW10	4.8	20.8	1	20.8	16.0
REW	5.0	20.0	8	2.5	1.9
RD	0.5	24.8	18	1.4	1.4
FD	2.5	22.2	18	1.2	1.1

*RW = Right Side Window
LW = Left Side Window
FD = Front Door
REW = Rear Escape Window
RD = Rear Escape Door

TABLE 3.28

TRIAL NUMBER 4
ANALYSIS OF OPENING TIME AND USE OF ESCAPE ROUTES

Exit Type*	Time to Open (Seconds)	Time of Last Escape (Seconds)	Number of Escapes	Time per Person Escaping from Exit (Seconds)	
				Including Opening Time	Excluding Opening Time
RW2	4.2	24.5	2	12.3	10.2
RW3	5.2	28.8	2	14.4	11.8
RW4	3.1	19.4	1	19.4	16.3
RW5	2.5	21.7	1	21.7	19.2
RW6	2.1	13.4	2	16.7	5.7
RW7	1.3	25.6	2	12.8	12.2
RW9	3.8	33.5	3	11.2	9.9
RW11	19.0	43.5	1	43.5	24.5
LW1	3.9	34.7	3	11.6	10.3
LW2	3.1	30.8	1	30.8	27.7
LW3	7.9	44.8	3	14.9	12.3
LW5	4.0	22.2	3	7.4	6.1
LW6	2.9	19.3	2	9.7	8.2
LW7	2.8	13.9	1	13.9	11.1
LW8	2.8	11.7	1	11.7	8.9
LW9	3.8	35.7	2	17.8	16.0
RD	8.3	57.3	34	1.7	1.4
REW	30.4	51.8	4	13.0	5.4

*RW = Right Side Window
LW = Left Side Window
FD = Front Door
REW = Rear Escape Window
RD = Rear Escape Door

TABLE 3.29

TRIAL NUMBER 5
ANALYSIS OF OPENING TIME AND USE OF ESCAPE ROUTES

Exit Type*	Time to Open (Seconds)	Time of Last Escape (Seconds)	Number of Escapes	Time per Person Escaping from Exit (Seconds)	
				Including Opening Time	Excluding Opening Time
RW2	4.5	29.7	2	14.8	12.6
RW4	2.5	22.6	3	7.5	6.7
RW6	2.3	11.5	2	5.8	4.6
RW7	1.5	11.4	1	11.4	9.9
RW8	3.5	29.8	3	9.9	8.8
RW9	3.8	19.4	2	9.7	7.8
RW11	1.3	25.4	1	25.4	24.1
LW2	1.6	28.9	2	14.5	13.7
LW5	3.0	25.0	2	12.5	11.0
LW6	2.1	14.9	1	14.9	12.8
LW7	5.3	24.7	2	12.3	9.7
LW8	4.0	15.2	1	15.2	11.2
REW	3.4	29.4	10	2.9	2.6
RD	3.8	29.2	16	1.8	1.6
FD	5.4	29.8	20	1.5	1.2

*RW = Right Side Window
LW = Left Side Window
FD = Front Door
REW = Rear Escape Window
RD = Rear Escape Door

slow, principally because of the restricted escape movements possible and the need for caution when escaping due to the height above ground level. The escape times obtained are significantly longer than those obtained for push-out windows tested under contract FH-11-7303 where the average escape time was 5.2 sec for comparable conditions.

The data for Trial 2 indicates that a large queue developed to escape from the rear window, since the smaller children would not use the side window escape routes. Spontaneous assistance was observed on this trial and others where older children who had escaped helped smaller children to the ground.

A comparison of escape times for the split-sash windows is given in Table 3.30. These times agree well, with the exception of the right windows on Trial 1 where one subject took 42 sec to make an escape. The average for the left side windows across all trials is 13.3 sec and 15.8 sec for the right side windows. However, if the first trial is deleted, the average escape time becomes 13.2 sec, thus agreeing well with the average time for the left side. These average times are more than twice as long as those obtained for pushout windows. It must be noted, however, that the pushout windows tested under contract FH-11-7303 (1) do not meet the latest NHTSA requirements for window retention.

It is possible to predict a total escape time for a school bus with a comparable subject group by using the average exit times and multiplying by the number of persons assumed to be escaping from each type of exit. The largest time value then becomes the controlling time value for the total escape time.

It is also possible, using this data, to speculate on the effects of escape drills on escape time where

TABLE 3.30

COMPARISON OF AVERAGE WINDOW ESCAPE TIMES

Trial Number	Average Escape Time, Including Opening (seconds)	
	Left Windows	Right Windows
1	14.7	26.5
2	13.9	15.3
3	11.6	11.6
4	12.5	15.0
5	13.6	10.7
Average All Trials	13.3	15.8

control is exercised over how many persons use each type of exit.

3.3.3.2 Intercity bus escape trial: The time data for the escape trials are presented in Table 3.31.

Trial 1 provides some insight into the escape time to be expected when passengers are unfamiliar with the escape routes and night vision is simulated. It also demonstrates that the passenger load utilized as subjects were able to effect an escape through only the windows, even though some subjects were above age 50. However, it must be remembered that only reasonably agile older subjects were chosen, since it was not believed that many older subjects could escape through a window without injury. The total escape time of 84 sec for Trial 1 was accomplished through only five pushout windows, since passengers were unable to open one window, and one window was partially blocked by the lavatory retrofitted to the bus. This window by the lavatory was later opened on Trial 3 and two passengers escaped through the restricted opening.

A comparison of the escape times for Trials 2 and 3 shows that the simulated night vision condition did not result in a longer escape time. It must be noted that this escape condition was preceded by a comparable escape under daylight vision so that subjects were already familiar with the escape procedure.

Table 3.32 shows the mean escape times and range of escape times for the intercity bus windows. It can be seen that a reduction of the mean time to open a window as well as the mean time to escape through a window occurred with successive trials. This result demonstrates that the escape time can be reduced by practice trials. However, it is likely that the time to escape on the first

TABLE 3.31

RESULTS OF INTERCITY BUS ESCAPE TRIALS

Trial Number	Number Subjects Escaping	Number Subjects Escaping from Each Exit (1)									Total Escape Time (Seconds)
		FD	RW1	RW2	RW3	RW4	LW1	LW2	LW3	RD	
1	38	-	0	8	0(2)	10	7	4	9	-	84.1
2	38	-	0	6	4	5	6	4	5	8	37.0
3	38(1)	-	2	4	5	4	7	5	4	7	31.6
4	38	8		1	3	4	4	5	5	8	21.8

(1) An attempt to open the window in position four adjacent to the lavatory was made on Test 2, but without success. Two passengers did succeed in opening this window on Trial 3 and escaping.

(2) Window was opened to position for ventilation, but passengers were unable to determine how to open window for escaping on this trial.

FD = Front Door RW = Right Window, numbered from front of bus
RD = Rear emergency exit door LW = Left window, numbered from front of bus

TABLE 3.32

TIME TO ESCAPE FROM INTERCITY BUS

Test Identification	Time to Open Windows (Seconds)			Time per Person to Enter and Escape through Windows (Seconds)		
	Mean Time	Shortest Time	Longest Time	Mean Time	Shortest Time	Longest Time
Trial 1	4.3	2.2	8.1	8.2	3.5	21.2
Trial 2	2.7	1.9	3.4	5.9	2.2	11.1
Trial 3	2.7	1.4	5.9	5.3	2.0	12.2
Trial 4	2.3	1.7	3.2	4.9	2.6	13.7

trial represents most closely the time which might be obtained under the best post-crash conditions. It is also evident that most of the improvement in window escape times occurred between the first and second trials.

A comparison of these times for window escape with those for the school bus shows that the times are significantly longer for the school bus. However, the times are comparable to those obtained for use of pushout windows on a school bus as reported under contract FH-11-7303 (1). This superiority of pushout windows can be attributed to their larger area for entering the window and escaping and their lower window sill height for entering the window from the bus interior as well as for dropping to the ground outside.

The time values for escape through the front and rear doors of the intercity bus are shown in Table 3.33. Superiority of the front door as an escape route is clearly shown, as compared to the rear door. Escape times through the rear door are greater than those for the school bus escapes as shown on Tables 3.25-3.29, but still only about half the time for a window escape.

Table 3.34 presents information showing the exit utilization for the intercity bus escape. It is obvious on each trial that a greater number of people could have escaped if there had been better utilization of the available exits. However, it is unlikely that an actual post-crash escape would have resulted in better exit utilization, taking into account the shock and panic which are likely to occur.

The debriefings conducted with each subject and detailed analyses of the escape movie films provided further insight into some of the subjects' reactions to escaping. These are summarized in the comments which follow.

TABLE 3.33

TIME TO ESCAPE FROM INTERCITY BUS

Test Identification	Time to Open Rear Door (Seconds)			Time to Escape Through Rear Door (Seconds)		
	Mean Time	Shortest Time	Longest Time	Mean Time	Shortest Time	Longest Time
Trial 1	-	-	-	-	-	-
Trial 2	3.1	3.1	3.1	2.0	1.1	3.0
Trial 3	1.9	1.9	1.9	2.8	1.7	3.6
Trial 4	1.6	1.6	1.6	2.3	1.3	3.2
	Time to Open Front Door (Seconds)			Time to Escape Through Front Door (Seconds)		
Trial 4	1.1	1.1	1.1	.8	.6	.9

TABLE 3.34

EXIT UTILIZATION FOR INTERCITY BUS

Test Identification	Time Exit Used and Number Escaping from Exit (Seconds)								Average Window Escape Time
	Windows						Doors		
	L1	L2	L3	R1	R2	R3	Rear	Front	
Trial 1	46.7/7	24.2/4	40.6/9	84.1/8	-	68.7/10	-	-	7.0
Trial 2	28.2/6	21 6/4	24.0/5	33.5/6	29.4/4	25.6/5	37.0/8		5.4
Trial 3	31.6/7	24.7/5	12.7/4	25.5/4	25.3/5	24.2/4	21/2/7		5.1
Trial 4	13.5/4	19.8/5	16.4/5	17.9/1	14.2/3	19.7/4	17.5/8	21.8/8	4.6

1. Most subjects were genuinely appreciative of the opportunity to participate and have the benefit of such experience should they ever need it.
2. The instructions for releasing the window latch to open it for escape were unclear or confusing, in that some subjects opened the window for ventilation, rather than releasing it for escape.
3. The windows were too heavy for many subjects to push out sufficiently to make a rapid escape, with this difficulty only overcome by spontaneous help from some of the male passengers holding the window open.
4. Several passengers inadvertently allowed windows from which they were escaping to fall back on the next person escaping, thus presenting a hazard. First-aid treatment was necessary for a variety of scrapes and bruises.
5. Size of the window for escape must be considered in relation to the height of the window from the ground. All adult subjects used the technique of climbing over the window sill and dropping to a position where they were still holding with their hands to the window sill, then dropping the remaining distance to the mattress placed to break their fall. It is evident that when the escape opening is reduced to the presently allowable minimum size of 13 in by 20 in (as provided for by Part 571--Federal Motor Vehicle Safety Standards--Bus Window Retention and Release) that escape will become much longer and injuries are likely to occur.
6. Children were always helped by their parents in making an escape. If this were not the case, then the heavy windows would make it very difficult for them to escape.

Presentation of conclusions and recommendations will be deferred until after the next two sections covering strength testing and escape analysis have been presented.

3.4 HUMAN STRENGTH STUDIES

An examination of the results of the bus escape tests discussed in Section 3.3 shows that the ability and time to open an exit for emergency escape were significant variables for any given escape trial. Direct observation of school children trying to open bus exits indicated that some types of exit latching mechanisms required more force than the child could produce. In order to establish performance standards for the operation of exits and their use, it was necessary to obtain some data on strength capabilities of children. Data are also needed on the strength required for the operation of passenger car door handles and bus window latches, especially when a collision has made the door latching mechanism difficult to operate.

3.4.1 Literature Review

The force capabilities of women in operating door handles was investigated (13); details are given in Appendix C.5. This investigation is one of a limited number of studies of female strength which have applicability to defining the operating force level for emergency escape exits.

Kroemer (14) has reviewed the literature recently on human strength measurement and provides a good summary of the existing literature. Others such as Chaffin (15) have developed biomechanical models to predict certain types of force capabilities for men and women. The NHTSA has recently contracted for a study of body segment parameters and strength capabilities for children and adults (16). Karim (17) and Leeper (18) have also reviewed the literature on female strength capabilities and conducted studies of forces which can be produced by females piloting a light airplane.

While a significant number of studies of human strength capabilities exist, it is still difficult to apply them directly to the problems of escape exit design. From the literature previously cited, a few major comments can be made:

1. Static strength capabilities (production of a force with no movement) for men and women producing forces with the upper limb while seated in such configurations as push-pull straight ahead, and up-down have been determined. Additional studies of men have been made for a variety of other limb positions, producing static forces while seated, with force applications in the left-right direction in addition to those previously mentioned.
2. Static strength capabilities for women and men have been studied by measuring elbow, shoulder, trunk and leg forces parallel to the mid-saggital plane and then integrating these force measurements into a predictive model for lifting with various limb and trunk positions.
3. Static muscular strength has been measured for momentary exertions (1-5 sec), and for extended periods with the force exerted being a percentage of the value obtained for momentary exertions. It is well known that an exponential relationship exists between a percentage of maximal momentary static strength and time the force level can be maintained.
4. Determination of force levels which can be produced while reaching around obstacles (such as seat backs to open a window), and in an unfavorable posture, obviously gives rise to a great many additional variables and can only be accomplished for very specialized experimental conditions.

5. Strength capabilities vary widely for both male and female populations, necessitating consideration of this strength range, rather than designing only for the mean strength values of the population.

3.4.2 Experimental Design and Procedure

The investigation of adult female strength in operating passenger car door handles referenced earlier and presented in Appendix C.5 provides some badly needed basic data and could be extended into several other types of strength measurement. However, the pressing need for strength data for boys and girls in the elementary grades who ride school buses dictated that child strength studies should receive the remaining allocation of funds for strength measurement. Thus, the test program described in the following sections was restricted to the measurement of strength of elementary school children, with the objective of gathering a specific set of data directly applicable to escape exit design.

3.4.2.1 Independent variables: There are many variables which can affect the capability to produce a desired force for operating an escape exit:

1. Personal variables such as age, height, weight, motivation, general health, and sex.
2. Anthropometric variables such as limb segment parameters, somatotype, limb position and trunk position.
3. Type of hardware to which the force is applied, such as the operating handle or lever design employed.

The variables chosen from this overall set for investigation in these experiments were body type, age, sex, type of force application and method of force application.

The ages of 6-11 were chosen as representing the least strong group of school bus riders and those who might have difficulty operating an emergency escape exit.

Using the anthropometric data for children from the last U.S. Department of Health, Education and Welfare Survey (19), an attempt was made to find male and female subjects who were representative of the 5th, 50th and 95th percentiles in terms of height and weight for ages 6-11. Since these heights and weights could not be reproduced exactly, they were characterized by the terms "small," "medium," and "large" for the respective percentiles. Actual values of height and weight for subjects are shown later when subjects are described.

The type of force application was chosen as a variable after reviewing the escape films and surveying opening forces required on local school bus exits. Pushing a rear emergency exit door open after it was released was found to be a problem, so this type of force application was chosen for study. Operation of the door release bar was difficult for some children, so this area was chosen for study. Within the scope of the door release study, it was noted that different designs of release bars required different grasps, so this additional aspect was chosen for study. Subjects pulled upward on the bar with both hands, in the palms up and palms down positions, and with the left hand in the palm down position, comprising three levels of this variable.

<u>3.4.2.2 Dependent variables</u>: The design of most emergency door exits is such that a test of static strength capability was considered the appropriate dependent variable to be measured. A static force measurement was thus made when subjects either pushed against a door to open it, or when they pulled up on a lever under the three different conditions of grasp described. The force

was measured as the maximal force which could be achieved in a momentary exertion which ranged from 1-5 sec.

3.4.2.3 Subjects: The subjects chosen for the strength tests were school children, as indicated earlier. They attended a school operated by the University of Oklahoma, and some had participated previously in the bus escape tests. Subjects were classified as "small," "medium," or "large" in accordance with the 5th, 50th and 95th percentiles of the U.S. Department of Health, Education and Welfare survey (19) of children's height and weight for ages 6-11. Table 3.35 shows the values used as guidelines in choosing the three classes of subjects. Table 3.36 shows the heights and weights of the children who participated in the test of strength for pushing on a bus door. Some children were unavailable for testing in some of the size categories, although most size categories were filled with a student whose height or weight was typical of the percentiles shown in Table 3.35.

Table 3.37 shows the heights and weights for subjects who participated in the strength tests for rear escape door handle operation. An attempt was made to use the same subjects for all strength tests, and this objective was largely achieved, as can be seen from a comparison of Tables 3.36 and 3.37.

3.4.2.4 Equipment: The measurement of force level for all of the strength tests was accomplished by using strain gages and a reference bridge system. An aluminum bar with strain gages attached served as a cantilevered beam to which the respective forces were applied. Suitable preamplifiers and a strip chart recorder were used in conjunction with the reference bridge circuit to measure the force levels applied to the aluminum bar. This

TABLE 3.35

NATIONAL HEALTH SURVEY OF CHILDREN'S HEIGHTS AND WEIGHTS BY PERCENTILES (19)

Sex and Age	Weight (Pounds) Percentiles			Height (Inches) Percentiles		
	5th	50th	95th	5th	50th	95th
Boys						
6 years	35	48	63	43	47	51
7 years	40	53	72	45	49	53
8 years	45	60	82	47	51	55
9 years	48	65	97	49	54	57
10 years	56	72	99	51	55	60
11 years	60	81	118	53	58	62
Girls						
6 years	34	47	64	42	46	50
7 years	37	52	73	45	49	53
8 years	44	59	85	47	51	55
9 years	47	66	102	49	53	58
10 years	54	75	110	51	56	61
11 years	60	84	128	53	58	69

TABLE 3.36

HEIGHTS AND WEIGHTS OF SUBJECTS PARTICIPATING IN TEST OF STRENGTH FOR DOOR PUSH

Sex and Age	Weight (Pounds) Sizes			Height (Inches) Sizes		
	Small	Medium	Large	Small	Medium	Large
Boys						
6 years	NA*	52	61	NA	48	51
7 years	41	59	70	46	50	53
8 years	NA	60	80	NA	52	52
9 years	NA	66	95	NA	53	57
10 years	56	75	103	51	54	58
11 years	60	76	120	53	58	64
Girls						
6 years	NA	51	63	NA	46	49
7 years	40	57	73	47	49	53
8 years	NA	57	81	NA	52	55
9 years	45	NA	99	50	NA	59
10 years	52	69	102	51	53	60
11 years	NA	76	NA	NA	57	NA

*NA--Subject not available on day of test for this size category.

TABLE 3.37

HEIGHTS AND WEIGHTS OF SUBJECTS PARTICIPATING IN TESTS OF STRENGTH FOR REAR ESCAPE DOOR HANDLE OPERATION

Sex and Age	Weight (Pounds) Sizes			Height (Inches) Sizes		
	Small	Medium	Large	Small	Medium	Large
Boys						
6 years	35	NA	54	42	NA	49
7 years	40	48	57	46	48	51
8 years	48	60	75	50	52	54
9 years	57	68	100	52	54	58
10 years	58	66	100	52	56	61
11 years	69	77	95	53	59	63
Girls						
6 years	40	48	57	45	48	51
7 years	48	50	60	47	49	53
8 years	44	65	70	48	51	54
9 years	68	71	78	54	55	57
10 years	55	70	92	53	55	57
11 years	63	90	103	55	61	63

instrumentation is fully described in Appendix C.5. Deadweight calibration methods were used for calibrating the aluminum bar to which the strain gages were applied.

Two experimental test stands were constructed for measuring the two types of forces; one for the door pushing task and one for the lever operation task.

The rear emergency exit door from a 1971 model Superior school bus was acquired and mounted on its hinges in a suitable frame. The aluminum bar was then mounted in the frame so that the force being applied to the face of the door would be measured. Thus, a force normal to the face of the door was measured for a static push where the door moved only 1/4 to 1/2 in. Since the door was hinged, a small, negligible resistance due to friction in the hinges, having a value of less than one lb for new, well-oiled hinges, was observed. A platform was constructed in front of the door so that when a subject stood on the platform ready to push the door he was at the same height as he would be in the school bus.

In order to measure strength available for lever handle operation, a special yoke was constructed for attachment to the aluminum bar instrumented with the strain gages. This design is shown in Figure 3.55. The two surfaces for grasping the yoke were fitted to simulate the two major types of door handle release bars used on buses. One type requires that force be applied to the flat side or width of a bar one in in width, with the edge of the bar facing the passenger at the door. The other type of release bar requires that a force be applied to the edge of the bar where the subject now faces the flat side or width of the bar.

The yoke for measuring force application was placed 28 in off the floor to approximate the height of release bars off the floor for school bus emergency exit doors.

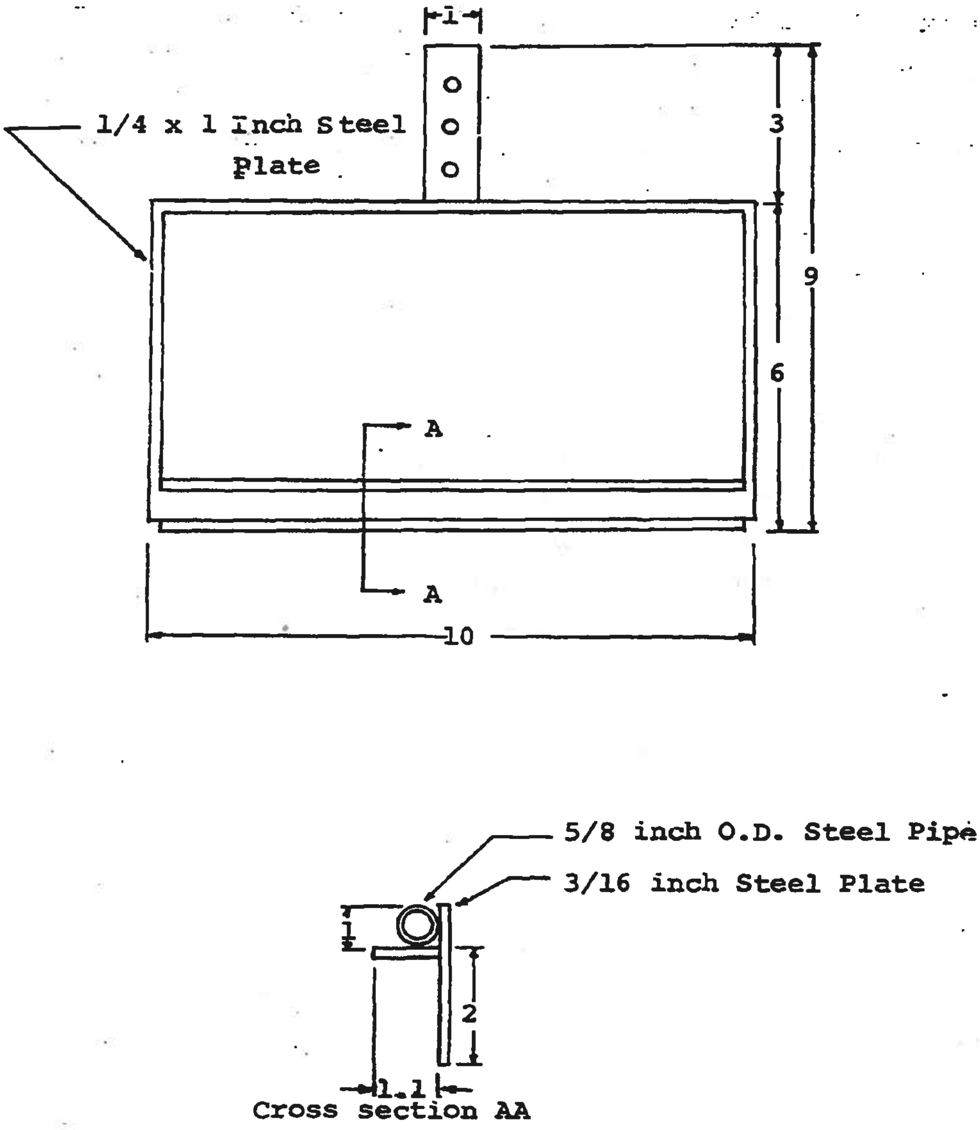

Figure 3.55. Yoke used as handle for strength measurement. Drawing is 1/4 scale.

Figures 3.56 and 3.57 show two views of subjects exerting a force on the yoke. The view shown in Figure 3.56 demonstrates the palms-down grasp over the edge of the bar which simulates one type of grasp necessary to operate some types of emergency exit door release handles. The other type of grasp shown in Figure 3.57 is with the palms up where the door structure causes an obstruction and results in a finger force exerted against the flat side or width of the door release handle.

3.4.2.5 Procedure: The apparatus for measuring strength of door push was transported to the premises of the school, was set up and was calibrated. Students had previously been selected for the tests and scheduled in groups for testing. Students were brought from their classroom in groups by their age, with all 6 yr, 7 yr, etc. ages tested together. They were weighed to check their reported weight used for selection, and corrections noted if necessary. They were also measured for height and corrections made if necessary. They then received the following instruction: "This machine will tell me how strong you really are. You will try to push this door open as hard as you can until I say 'stop.' OK? Ready, go! Good!"

This procedure was followed until all trials were complete, at which time the apparatus was checked again for proper calibration. The apparatus was then removed back to the research facility and the data reduced for all the tests.

Using the same strain gage, force measurement principle, the apparatus was reconstructed over a period of weeks to perform measurements for lever handle operation and transported back to the school. An additional attempt was made to find subjects for all size and age

Figure 3.56. View of subject exerting a force with the palms-down type of grasp on door release handle.

Figure 3.57. View of subject exerting a force with the palms-up type of grasp on door release handle.

categories, after which all categories except one were filled. Subjects were again weighed and their height measured to check the values which had been used in selecting the subjects, and the equipment calibration was checked.

Subjects were brought to the room for testing by age groups, one group for each of the years of 6-11 represented. When each subject stepped up for testing, he or she was given the following instruction: "This machine will tell me how strong you really are. You will jerk on this handle three different times. I will show you how to put your hands on it each time. Put your hands just like this. (Researcher demonstrated grip to be used.) OK, now when I say go, you jerk up and pull as hard as you can. OK? Ready, go! Good! Now put your left hand just like this. (Researcher again demonstrated grip to be used, and the same procedure continued until all three measurements were taken.)"

After testing all subjects, the equipment calibration was again checked before it was removed again to the research facility. Data reduction was again accomplished to convert the chart recordings to pounds of force exerted by each subject.

3.4.3 Results

The strength data obtained will be presented in two parts in the next sections. Data for the door push tests will be presented first, followed by the strength data for exit handle operation.

<u>3.4.3.1 Strength for pushing open exit door</u>: Table 3.38 shows the force levels available from the subjects tested for pushing open an emergency exit door. The wide differences in strength between age groups is

TABLE 3.38

STRENGTH DATA FOR PUSHING OPEN EMERGENCY EXIT DOOR

Age and Sex	Push Force (Pounds) by Subject Size Category			
	Small	Medium	Large	Mean Value for Group
Boys				
6 years	NA	15	18	16.5
7 years	13	18	28	19.7
8 years	NA	19	35	17.5
9 years	NA	26	30	28.0
10 years	48	61	74	46.3
11 years	51	92	111	84.7
Girls				
6 years	NA	18	23	20.5
7 years	10	13	13	12.0
8 years	NA	12	26	19.0
9 years	27	NA	38	32.5
10 years	23	27	36	28.7
11 years	NA	51	NA	51.0

$\bar{X}$ (mean value) for all data = 34.1 pounds

σ (standard deviation) for all data = 24.8 pounds evident, and was expected. This data demonstrates the need to consider the population of children who ride school buses in evaluating the capability of children to open an emergency exit.

It was found that the minimum force level required to open a pushout window under work performed on contract FH-11-7303 (1) was 108 lb under static loading. Thus, opening the window would require more force than could be exerted by all but one of the subjects, and yet the window would be unsatisfactory for retaining passengers in the bus during a crash.

While there are apparent differences in strength between boys and girls of the various ages, these differences are not statistically significant. It is known that adult females are 60 to 70 percent as strong as adult males as reported in References 17 and 18. Since data was not obtained for the age interval from 11 yr to adulthood, it is not possible to identify when the strength differential between males and females becomes apparent in this age interval.

In order to test the relationship for strength of push versus age for boys and girls, a linear regression line was fitted by the method of least squares, using the mean force level for each age across the three size groups. The data and the linear regression line of best fit are shown for boys and girls in Figure 3.58. A linear regression line fits the data for girls reasonably well, but does not fit the data for boys well. An exponential fit for the strength data for boys seems more appropriate but the small number of measurements for the ages represented will not allow a satisfactory test of this fit. Also, the later strength data presented indicate a significant linear relationship between strength and age, so these data may only represent an anomaly in the sample measured.

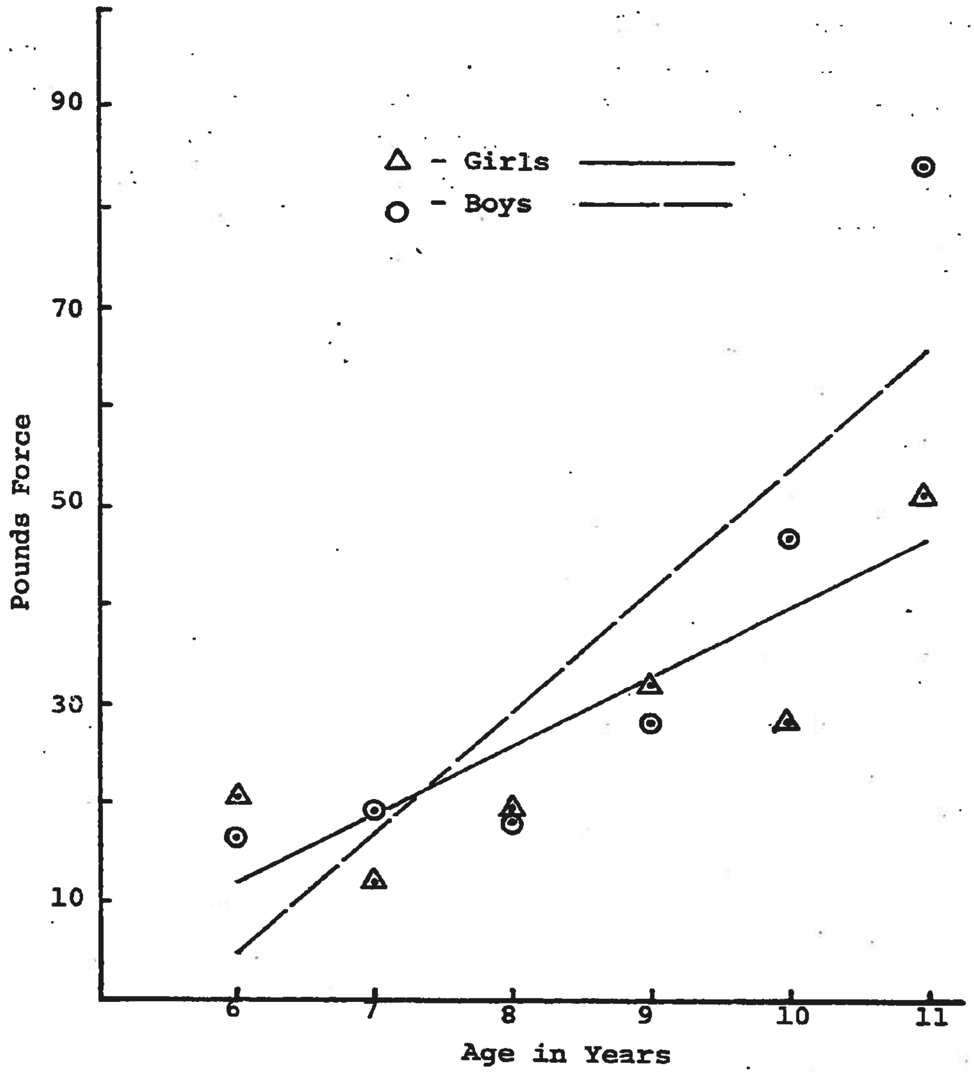

Figure 3.58. Plot of mean subject force levels produced for push on school bus exit door versus age of subjects for boys and girls.

3.4.3.2 Strength for pulling door release handle: Table 3.39 shows the strength data for pulling upward on a door release handle with the palms upward and the fingers pressing upward on a release bar. There is a progression of strength upward from the small size category to the large size category when the mean values are compared, although there were reversals of this relationship within individual size categories. A least-squares linear regression line was fitted to the mean values of strength for boys and girls, as shown in Figure 3.59. In this case the relationship between strength and age was found to be significantly linear for both boys and girls, as can be seen from Figure 3.59. It is also apparent that body size category is not a good predictor of strength for the subjects tested.

Table 3.40 shows the strength data for pulling upward on a door release handle with the palms down and the fingers grasping the lower edge of the bar used as a release handle. It is immediately apparent that this type of grasp allows more force to be exerted than the palms-up type of grasp which is required in the operation of some exit release handles. In the palms-up type of grasp, the fingers must bear most of force load while in an unfavorable position. This type of force application is also similar to that which would be required to operate the release bar for the window on most intercity buses.

A plot of strength versus age for the type 2 grasp is shown in Figure 3.60. A significant linear relationship between strength and age for boys and girls is again apparent. Little difference in the strength of boys versus girls is again the result as had been observed previously.

Table 3.41 shows that almost as much force can be exerted with one hand in the palms-down type of grasp as with both hands in the palms-up type of grasp. It is also apparent that the better type of grasp will allow greater than one-half the force level to be exerted which could be exerted with both hands. This result is expected, since leg, back and arm strength all enter into the production of a force, with the grasp strength becoming a controlling factor.

A plot of the data for grasp number 3 as shown in Figure 3.61 again indicates that a significant linear relationship exists between strength and age for both boys and girls.

Conclusions and recommendations for this section will be incorporated at the end of the following section which presents an overall analysis of bus escape worthiness.

TABLE 3.39

STRENGTH FOR PULLING DOOR RELEASE HANDLE
GRASP NUMBER 1*

Age and Sex	Pull Force (Pounds) by Subject Size Category			
	Small	Medium	Large	Mean Value for Group
Boys				
6 years	18	NA	19	18.5
7 years	22	20	36	26.0
8 years	34	43	41	39.3
9 years	52	48	68	41.3
10 years	56	47	88	63.7
11 years	66	72	95	77.7
Girls				
6 years	18	21	26	21.7
7 years	21	21	39	27.0
8 years	34	46	44	41.3
9 years	52	43	63	52.7
10 years	64	58	61	61.0
11 years	65	100	89	85.7

*Pull exerted on bar using a grasp with palms upward and fingers pressing upward on flat surface of 1 in bar.

$\overline{X}$ (mean value) (all sizes and ages) = 48.2 pounds

σ (std. deviation) (all sizes and ages) = 23.0 pounds

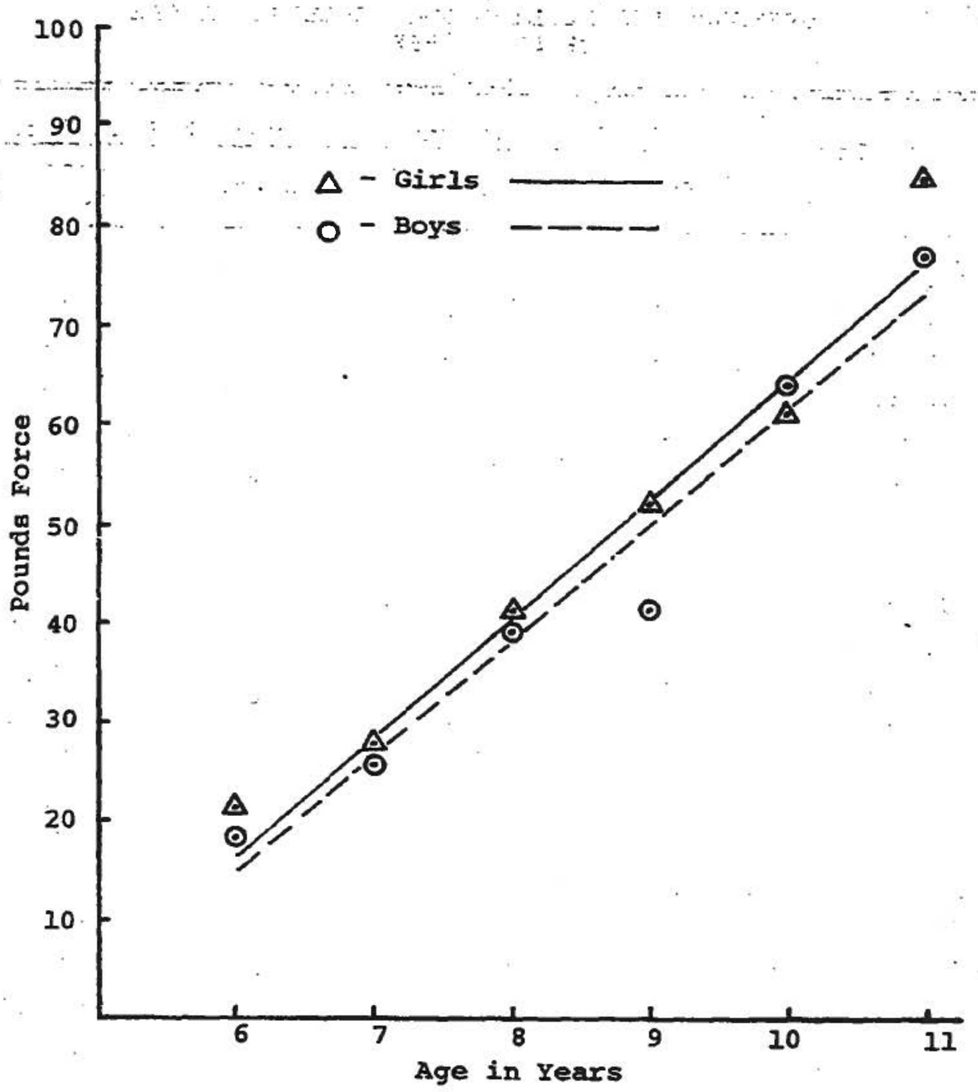

Figure 3.59. Plot of subject force levels produced for pulling door release handle using grasp number 1 versus age of subjects for boys and girls.

TABLE 3.40

STRENGTH FOR PULLING DOOR RELEASE HANDLE
GRASP NUMBER 2*

Age and Sex	Pull Force (Pounds) by Subject Size Category			
	Small	Medium	Large	Mean Value for Group
Boys				
6 years	20	NA	27	23.5
7 years	24	37	49	36.7
8 years	50	50	53	51.0
9 years	64	62	80	68.7
10 years	62	68	100+	76.7
11 years	89	92	100+	93.7
Girls				
6 years	28	36	29	31.0
7 years	28	37	47	37.0
8 years	37	60	61	52.7
9 years	64	46	73	61.0
10 years	64	60	81	68.3
11 years	85	100+	100+	95.0

*Pull exerted on bar with both hands, palms down and fingers grasping lower edge of bar used as release handle.

$\overline{X}$ (all sizes and ages) = 58.8 pounds

σ (all sizes and ages) = 24.1 pounds

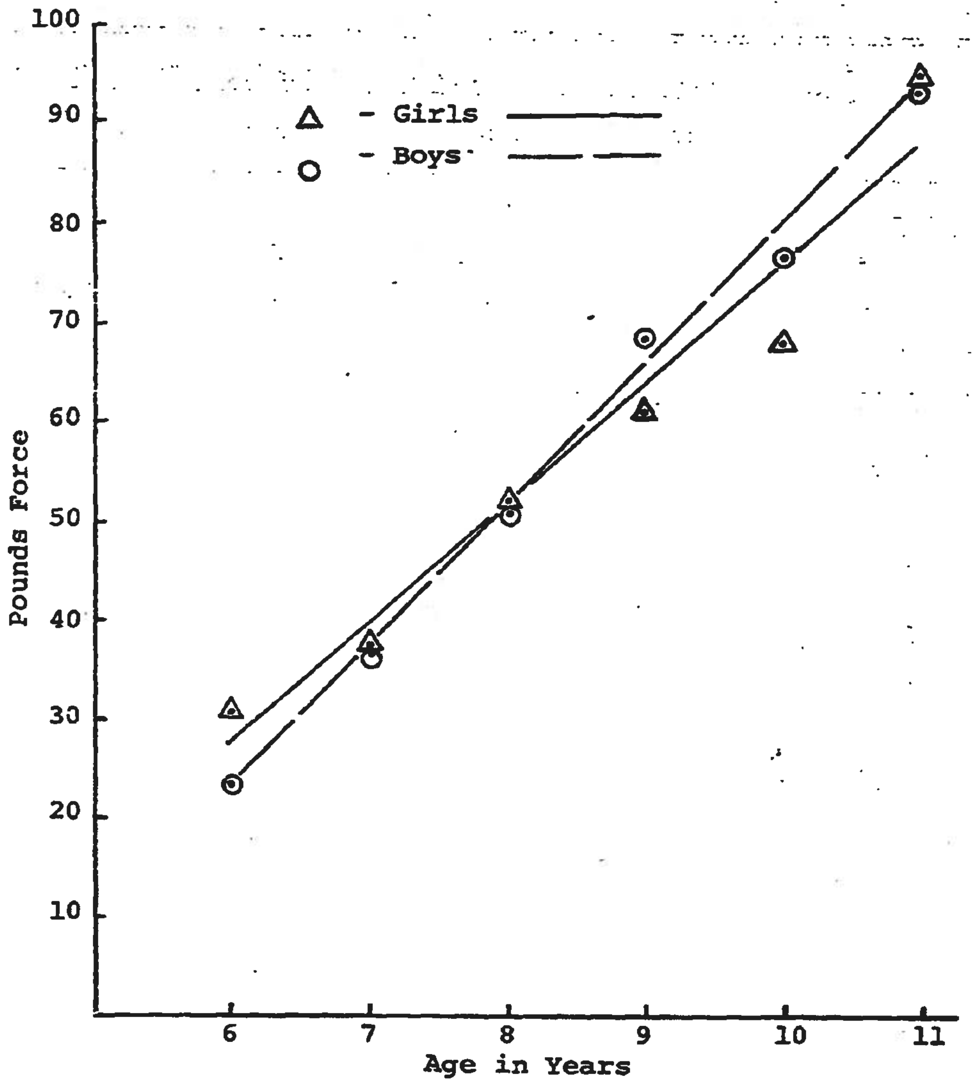

Figure 3.60. Plot of subject force levels produced for pulling door release handle using grasp number 2 versus age of subjects for boys and girls.

TABLE 3.41

STRENGTH FOR PULLING DOOR RELEASE HANDLE GRASP NUMBER 3*

Age and Sex	Pull Force (Pounds) by Subject Size Category			
	Small	Medium	Large	Mean Value for Group
Boys				
6 years	12	NA	19	15.5
7 years	19	25	42	28.7
8 years	30	36	40	35.3
9 years	47	47	60	51.3
10 years	45	48	88	60.3
11 years	63	70	100	77.7
Girls				
6 years	19	19	24	20.7
7 years	21	26	31	26.0
8 years	32	44	46	40.7
9 years	51	44	60	51.7
10 years	48	57	66	57.0
11 years	66	88	97	83.7

*Pull exerted with left hand only, palm down and fingers grasping lower edge of bar used as release handle.

$\overline{X}$ (all sizes and ages) = 46.5 pounds

σ (all sizes and ages) = 23.0 pounds

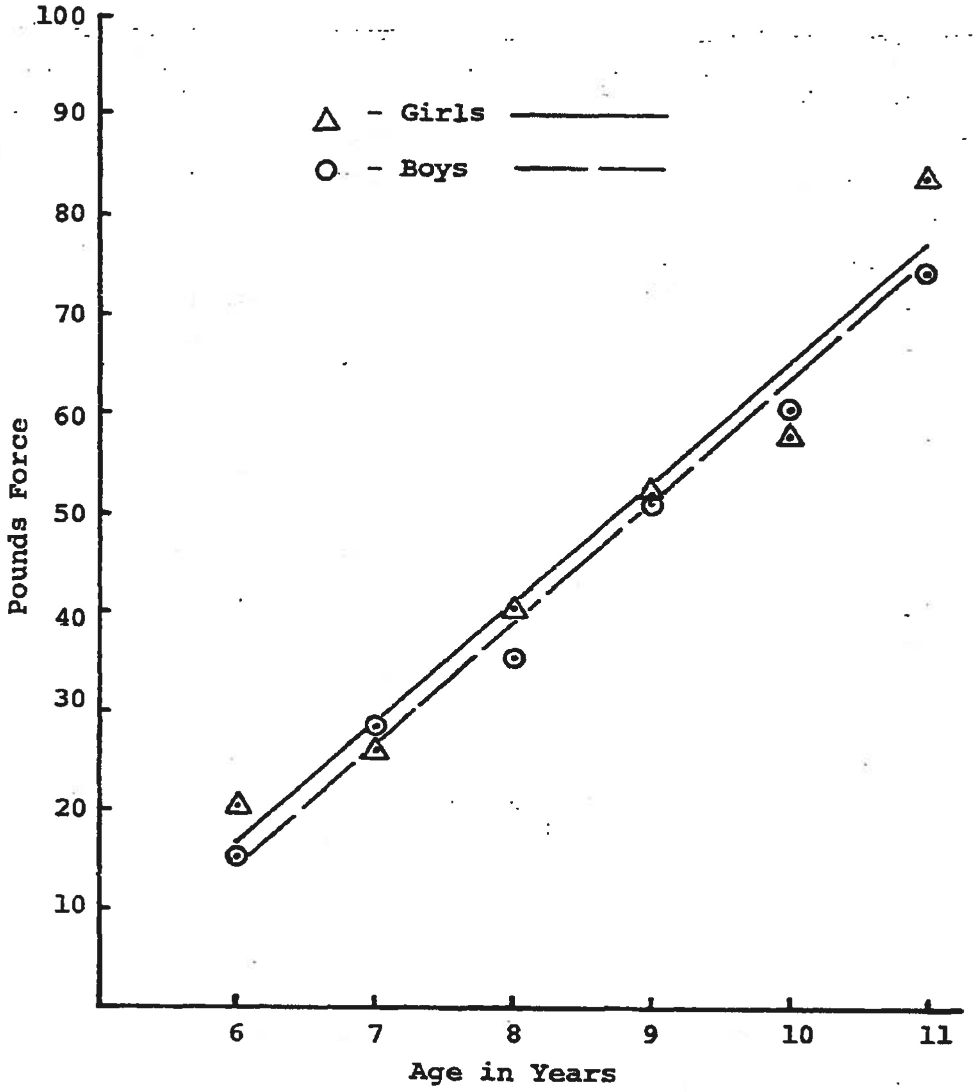

Figure 3.61. Plot of subject force levels produced by pulling door release handle using grasp number 3 versus ge of subjects for boys and girls.

3.5 ANALYSIS AND SUMMARY OF BUS ESCAPE WORTHINESS

Previous sections in this chapter have dealt with the studies of escape from school buses and intercity buses, and with the measurement of human strength in order to provide data needed for designing and evaluating bus escape exits.

This section will provide further insight into additional problems of bus escape worthiness, and will illustrate the relevance of the two former sections by focusing on some specific buses which have been analyzed for escape worthiness. The section also includes conclusions and recommendations relating to bus escape worthiness.

An explanation of the relationship between material contained in this section and the recently published (Federal Register, May 10, 1972, pp. 9394-97) Federal Motor Vehicle Safety Standard, Part 571, Bus Window Retention and Release is necessary in order to properly interpret the results presented. The data which is presented for intercity buses currently in use was developed prior to publication of the Standard, and must be viewed in that context. An attempt has been made to relate the data presented to the provisions of the new Standard, which appeared while this final report was being prepared.

3.5.1 Analyses of Intercity Bus Escape Worthiness

The major types of intercity buses currently in use were selected for escape worthiness analysis. These buses are manufactured by three different companies and encompass five different models. The Silver Eagle bus model is manufactured in Belgium and imported for use in this country. The Challenger bus model is manufactured by the Greyhound Corporation for their own use. The PD4106, PD4107 and PD4905 bus models are all manufactured by General Motors and generally used in intercity bus transportation.

Figures 3.62 through 3.66 show views of these buses for reference in the following sections where the escape worthiness of each bus is analyzed. In the analysis of each bus, the type of exits discussed is restricted to those which are acceptable under the new standard for Bus Window Retention and Release of Part 571, Federal Motor Vehicle Safety Standards. While some areas of window and windshield glazing could serve as an escape exit when the glazing has been removed, this type of exit does not meet the requirements of an escape exit under the referenced standard. School bus emergency exits are also excluded under this standard.

3.5.1.1 The Silver Eagle bus model: This bus is designed to carry 46 passengers (when equipped with a lavatory). The new Bus Window Retention and Release standard specifies that at least 67 square in of unobstructed opening be available as an emergency exit for each passenger seat on the bus. This standard would require 3082 square in of area, which are already available on the current Silver Eagle, since it has 12 windows having a dimension of 21 in by 49 in and two windows having a dimension of 21 in by 26 in. In addition, the standard requires that at least 40 percent of the required area be available on each side of the bus, and that no more than 536 square in can be credited for any one escape exit. Both of these requirements are also currently satisfied.

The new standard also specifies that at least one "rear exit" be provided, or if this is not feasible, then

Figure 3.62. View of Silver Eagle model of bus manufactured in Belgium.

Figure 3.63. View of Challenger (Scenic Cruiser) model of bus manufactured by the Greyhound Corporation.

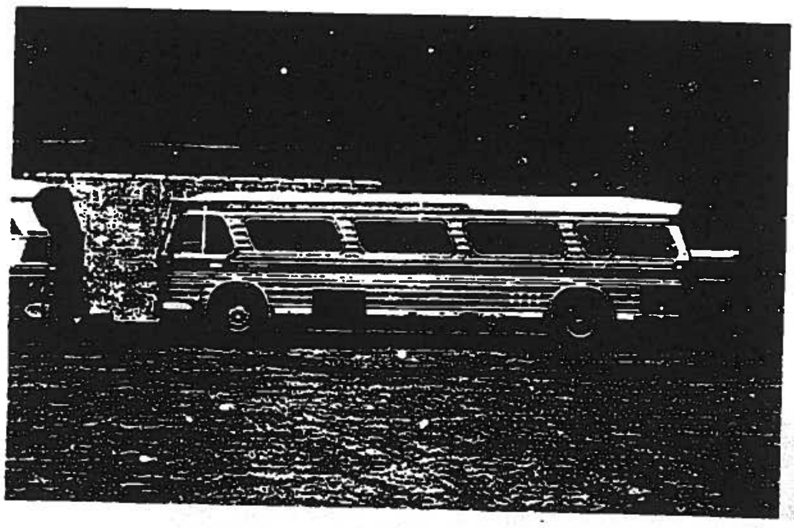

Figure 3.64. View of Model PD 4106 type of bus manufactured by General Motors Corporation.

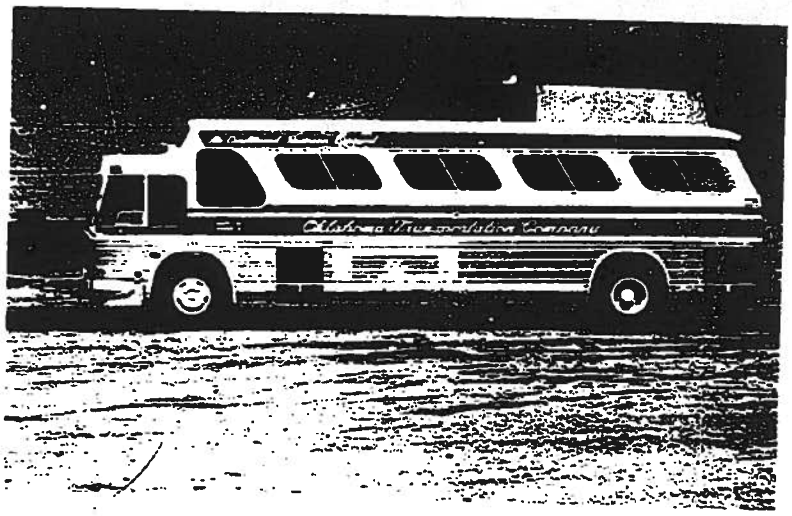

Figure 3.65. View of Model PD 4107 type of bus manufactured by General Motors Corporation.

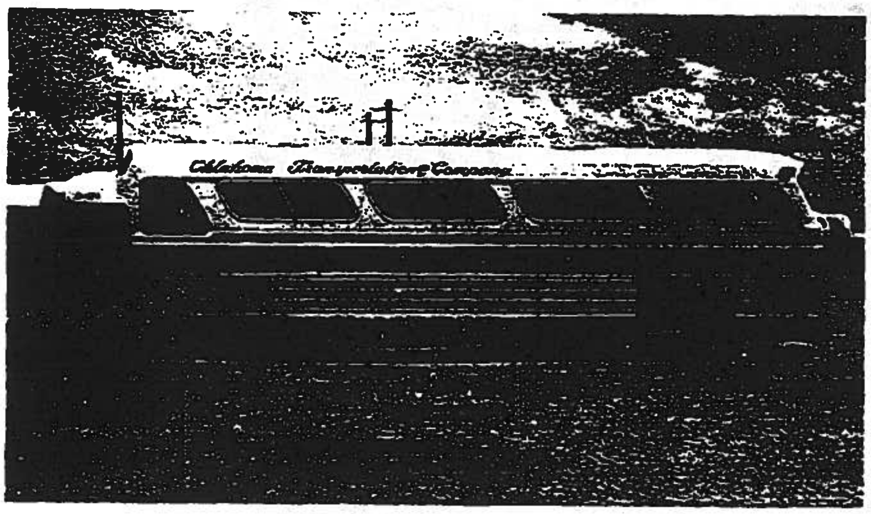

Figure 3.66. View cf Model PD 4905 type of bus manufactured by General Motors Corporation.

a "roof exit" must be provided. This specification requires interpretation, since the two terms are not adequately defined. The Silver Eagle would not meet this requirement unless a rear push-out window is considered as a "rear exit."

Escape through the side windows of the Silver Eagle involves two steps. First, a latch mechanism as shown in Figure 3.67 must be released as shown in Figures 3.68 and 3.69. The latch required a large amount of force to open, and as shown in Figure 3.70, it was possible to insert only two fingers inside the 1 3/4 in long latch handle. A latch mechanism was located near each lower corner of the window so that two latches had to be released before the window could be opened. These latches were separated by the adjacent seat back and required either the cooperation of the two passengers sitting ahead of and behind the seat back, or required one of the passengers to stretch over the next seat back to release the other latch. The rear latch could not be seen by the front passenger and the front latch could not be seen by the rear passenger in some seating arrangements as shown in Figure 3.71. Next, the window is pushed out at the bottom (it is hinged at the top) by overcoming a friction force fit. Once the window has been pushed out, another hazard exists. Although the corners of the windows are rounded and do not present a sharp obstacle for the escaping passenger, the latch mechanism which is attached to the window as shown in Figure 3.69 can strike the passenger as he exits the window. This would concentrate the entire moment force (or mementum) at this one point. As an example, if the window is opened at an angle of 45 degrees from the vertical, the center of gravity of the window is raised approximately 20 in. Releasing the window will cause it to slam shut in approximately 0.2 sec

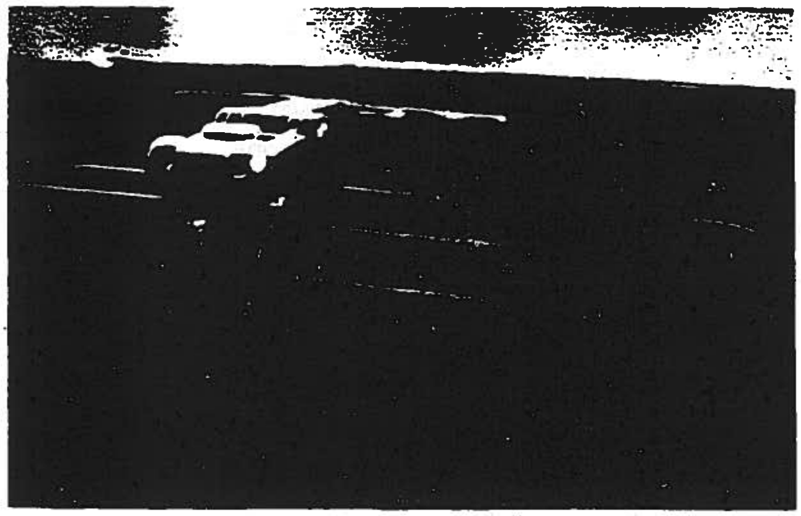

Figure 3.67. View of window latch for Silver Eagle bus model.

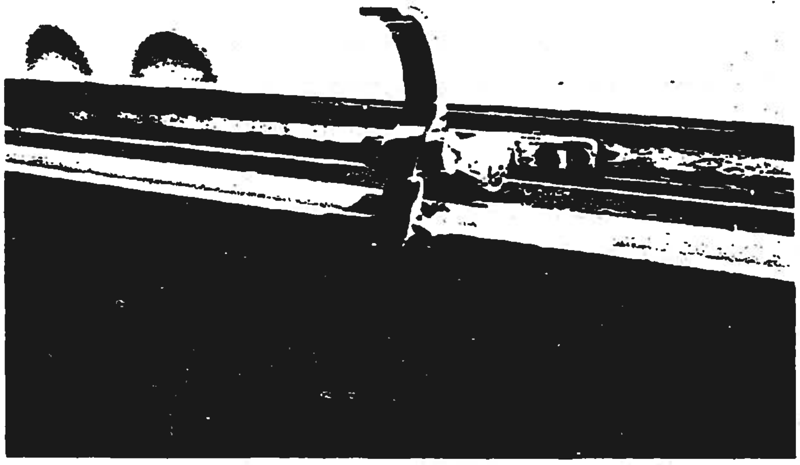

Figure 3.68. View of window latch on Silver Eagle bus model partially released.

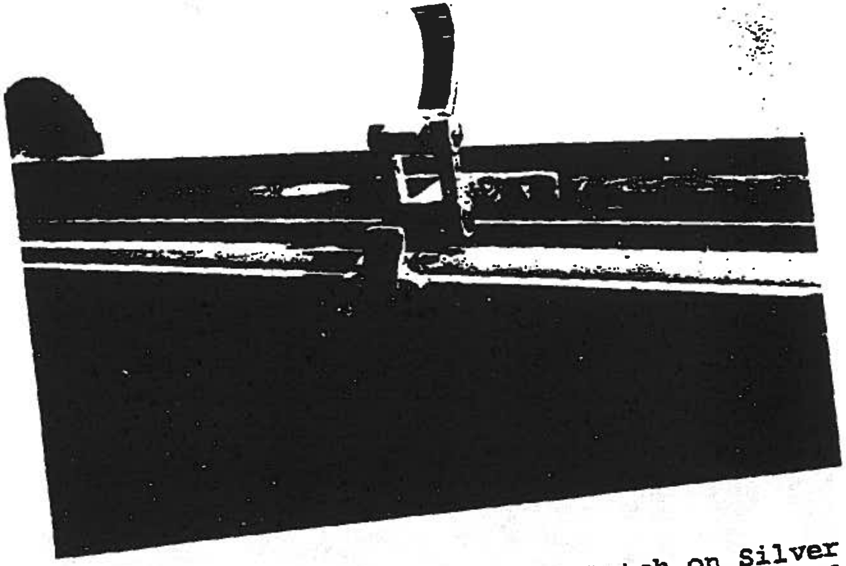

Figure 3.69. View of window latch on Silver Eagle bus model fully released.

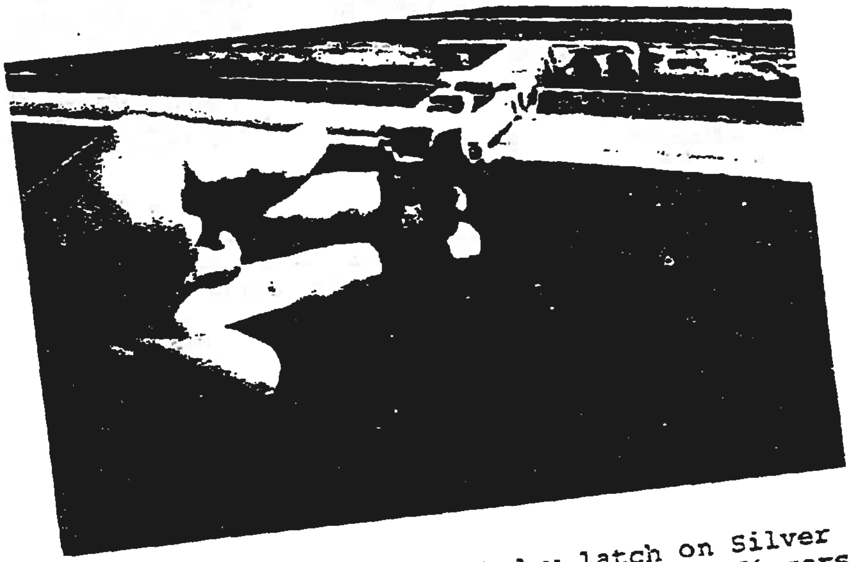

Figure 3.70. View of window latch on Silver Eagle bus model showing fingers inserted for pulling on latch.

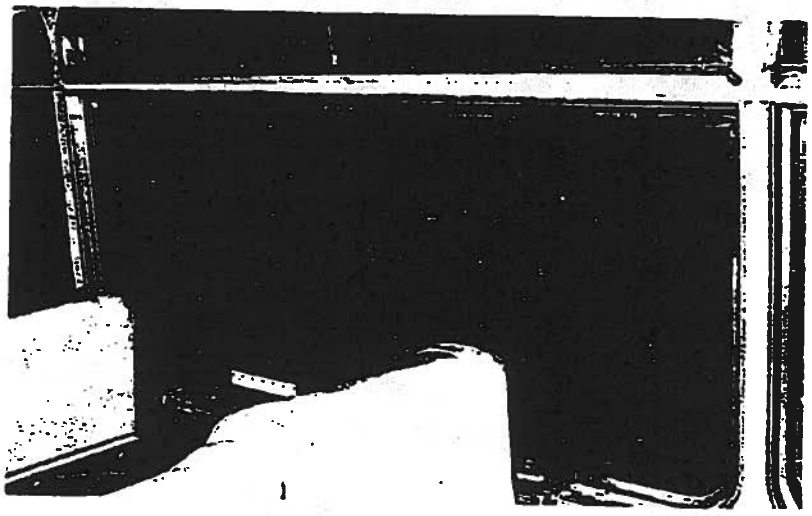

Figure 3.71. View of window latches on Silver Eagle bus model showing adjacent seating positions.

with a final velocity of 3.2 ft per sec. This translates into a force of momentum of 96 ft-lbs (using 30 lbs as the window weight). This amount of force would be concentrated on one point of the subject (perhaps his head or hand) and is sufficient to cause injury. A recommendation is made later in this section to eliminate this hazard. Once the window is open, the passenger has a drop of 7 ft, 2 in from the window to the ground. The passenger probably would hesitate for a short time while he estimated the difficulty. This hesitation will allow the window time to slam shut unless it is being held by another passenger. The drop of over seven ft is also a hazard and could easily cause injury, especially to passengers not accustomed to such maneuvers.

It was not possible to obtain an accurate measure of the force level required to open the window latch, so it is not known whether the operating forces are within the limits specified in the Bus Window Retention and Release standard of 20 lbs for the low force application area and 60 lbs for the high force application area. Since this type of latch requires a rotary motion or torque application, the specified maximum level of 20 in lbs would apply.

If the bus is on its side, other problems appear. The window now can be pushed open more than ninety degrees, so it would not present the danger of slamming shut on the exiting passengers. The passengers would probably have difficulty in pulling themselves up through the window since the width of the bus is eight ft. It would be possible for the passengers to form a type of stair-step system with the arms of the chairs, and by proper positioning of the seat backs of the chairs. The strengths of the chairs to this direction of force is not known with accuracy, but since they are not designed for this type of use, it is apparent that failure may occur after much weight is applied, especially if the passenger takes a slight jump to help him exit through the window above him. Once the passenger has exited the window, he finds himself eight feet above the ground. He has the choice of trying to crawl down the underside of the bus, or to slide or jump. Due to the sharp objects and numerous hazards of the bus undercarriage, this would be a poor method of escape. The better method would be to assume a sitting position at the roof of the bus and then slide. The bus has a rounded top which would facilitate this method of escape to the ground. This route would serve to help reduce injuries and the friction of sliding would slow the descent, thus making impact with the ground less for the passengers using this escape route.

3.5.1.2 The Challenger bus model: Applying the same sections of the Bus Window Retention and Release standard to the Challenger as was performed for the Silver Eagle model in Section 3.5.1.1, the Challenger meets the window area requirements, having 10 windows with an average area of 1667 sq in each. It has a passenger capacity of 39 persons when equipped with a lavatory. It does not meet the requirement of providing a "rear exit" or "roof exit" as required by the standard.

Two different types of side window openings are found on the Challenger buses. The first type, and apparently older design, consisted of a release bar which had to be lifted, as shown in Figure 3.72, before the lower portion of the window could be pushed out. The newer design has a similar release bar, but before the window can be pushed out a cable release has to be pulled as shown in Figure 3.73. The cable was observed to catch under the rail lip and was only slightly visible from the adjacent passenger seat. Only after the cable was freed from the

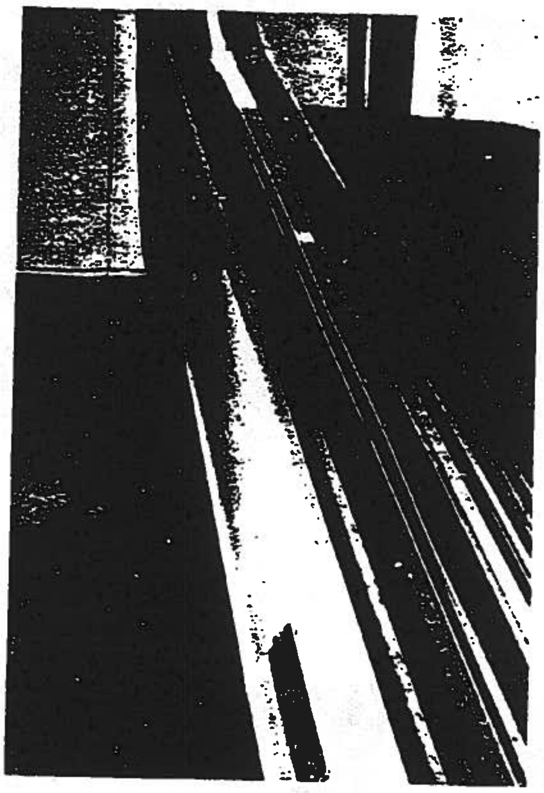

Figure 3.72. View of side window release bar pulled upward for releasing window on Challenger bus model.

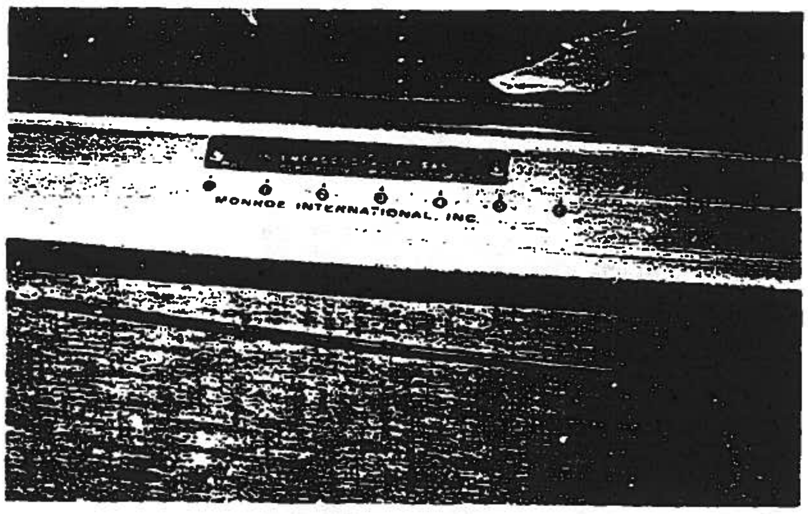

Figure 3.73. View of side window release bar pulled upward for releasing window, showing cable which must be pulled to finish releasing the window for Challenger bus model.

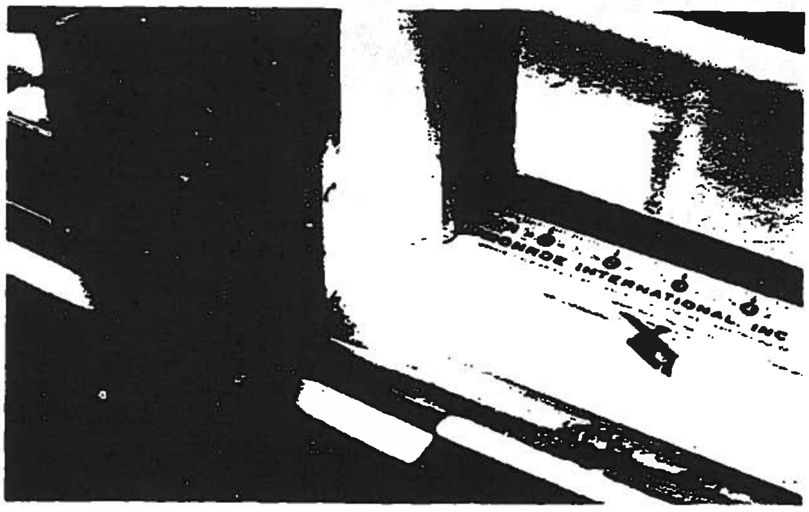

Figure 3.74. View of sharp corner on side window of Challenger bus model. Also note the sharp point on the cable attachment point.

rail lip could it be seen as shown in Figure 3.73. The instruction labels for operating each type of window latch were clearly illustrated, provided the cable in the newer design was visible after the bar was pulled up. If the cable was not released, the window would only open so the bottom of the window frame was about four inches from the bus body. The force levels required to operate the release bar or to pull the release cable could not be measured to determine whether they are in compliance with the standard on Bus Window Retention and Release. The drop to the ground was 6 ft, 10 in from this window.

Each of the windows on the Challenger had at least one very sharp 90 degree corner as shown in Figure 3.74. The cable release latch presented the same striking hazard as the release lever on the Silver Eagle, where a window dropping back on a passenger could produce an injury.

If the bus were on its side, the same techniques and obstacles discussed in the section on the Silver Eagle would apply. Again, it would be possible to slide off the top rounded portion of the bus.

<u>3.5.1.3 The PD4106 bus model</u>: The PD4106 bus model has eight windows in a parallelogram shape which can be used for escape, each having a dimension of 52 in by 24 in. The bus has a seating capacity of 39 when lavatory equipped and would comply with the window area requirements of the Bus Window Retention and Release standard. It does not have a "rear exit" or "roof exit" as specified by the standard.

The side windows have rounded corners and would not present the striking hazard found on the Challenger if they were allowed to fall on a passenger.

The side windows on the PD4106 are released by depressing two plastic buttons which project from the lower corner of each side window as shown in Figure 3.75. When these plastic buttons are depressed, a pin is released within the window and then the window can be pushed out. This type of release would require the coordinated effort of two passengers or would require a reach over the next adjacent seat, or walking around to the next seat. As in the Silver Eagle, the forward passenger may not know another release exists and the rear passenger may not be able to see the forward release. No instructions were provided for release on this model.

Exit through the window after opening would proceed as on the Silver Eagle. The drop to the ground from the window was measured to be 5 ft, 9 in (the lowest of any bus measured). If the bus were on its side, the passengers could slide off the bus as discussed in the section on the Silver Eagle, provided they could escape from the windows eight ft overhead.

Force levels for operating the window latches could not be measured to determine whether they are in compliance with the Bus Window Retention and Release standard.

3.5.1.4 The PD4107 bus model: The PD4107 bus model has eight windows which can be used for emergency escape, each in the shape of a parallelogram having a dimension of 52 in by 24 in. It has a capacity of 39 passengers when equipped with a lavatory, and therefore meets the requirements of the new standard for emergency exit windows. It does not have a "rear exit" or a "roof exit" as the standard requires.

The side windows for the PD4107 can be opened by two different methods. One method is to release a retainer as shown in Figure 3.76 and slide the window open along the wall of the bus. The opening of this window in this manner will form an exit area of almost one-half of the

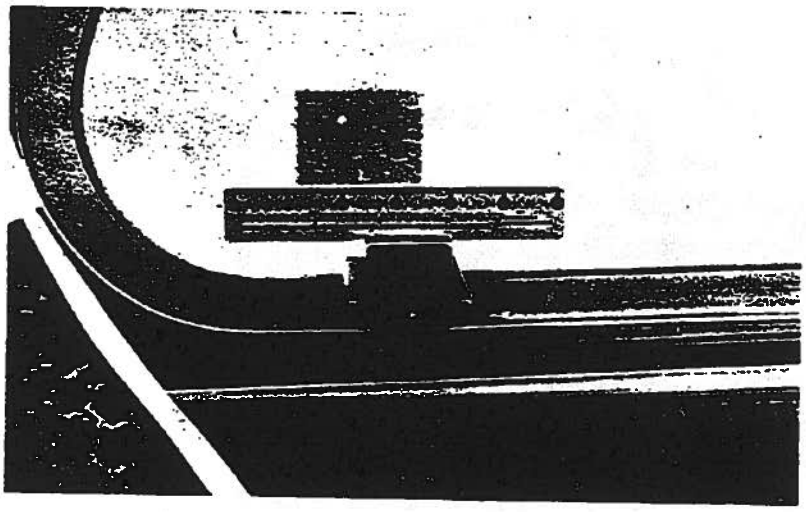

Figure 3.75. View of side window release latch for PD 4106 bus model.

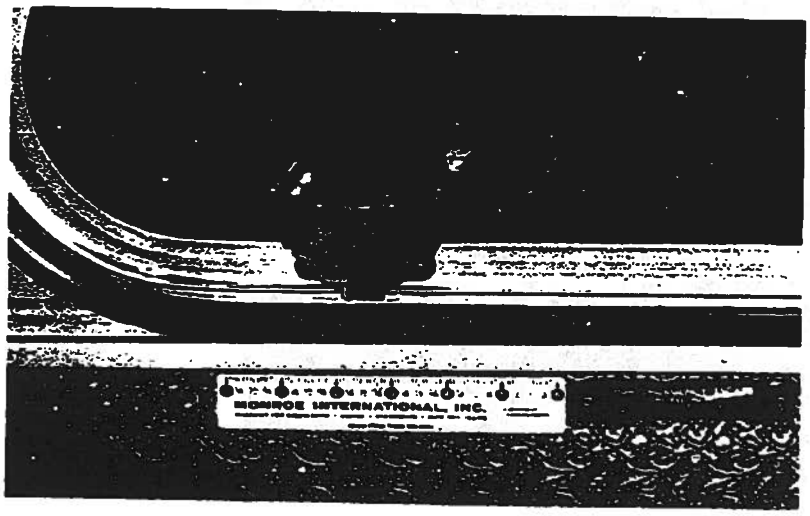

Figure 3.76. View of side window release latch for opening to obtain ventilation on PD 4107 bus model.

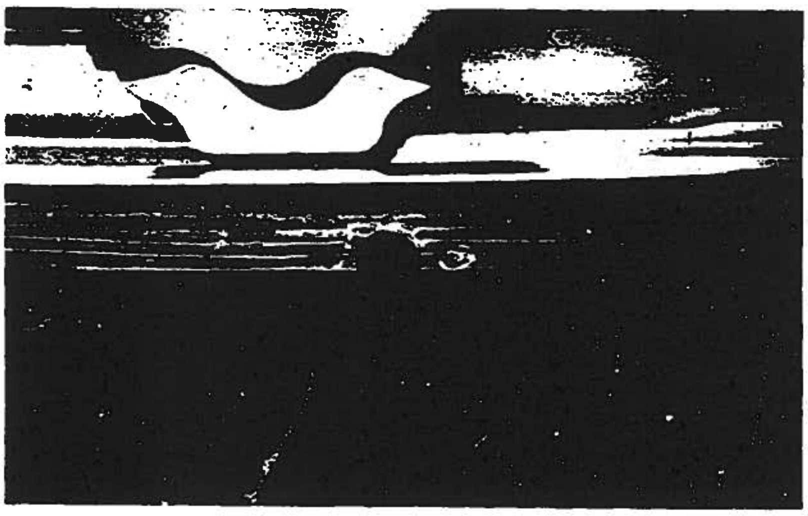

Figure 3.77. View of rubber grommet in side window of PD 4107 bus model. A plunger is pushed into this grommet to fasten the window.

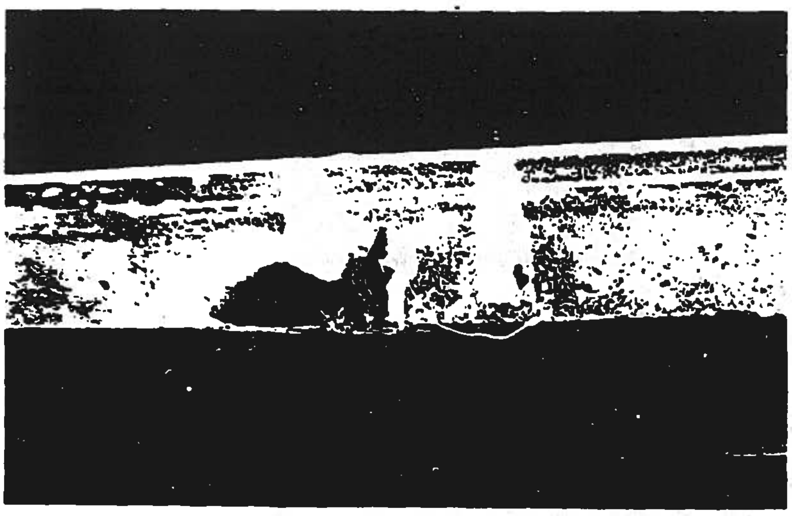

Figure 3.78. Top view of window sill and metal plunger for insertion into rubber grommet on bus side window on the PD 4107 bus model.

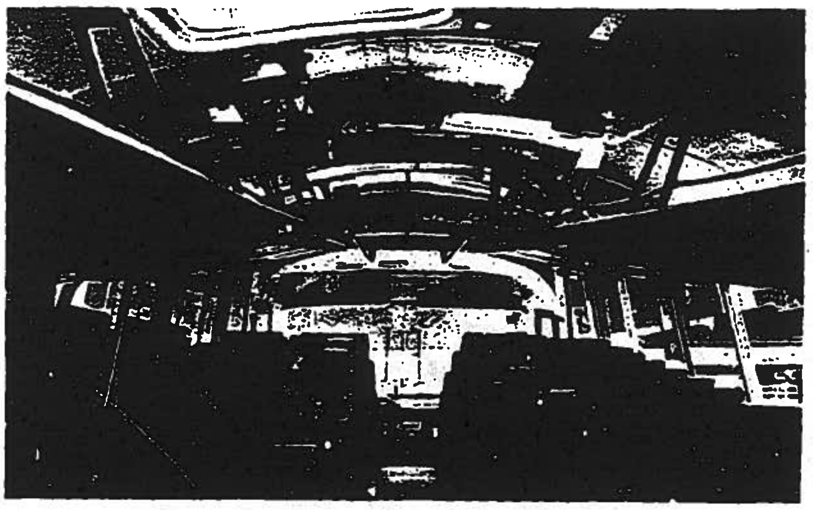

Figure 3.79. View of roof hatches on PD 4905 bus model.

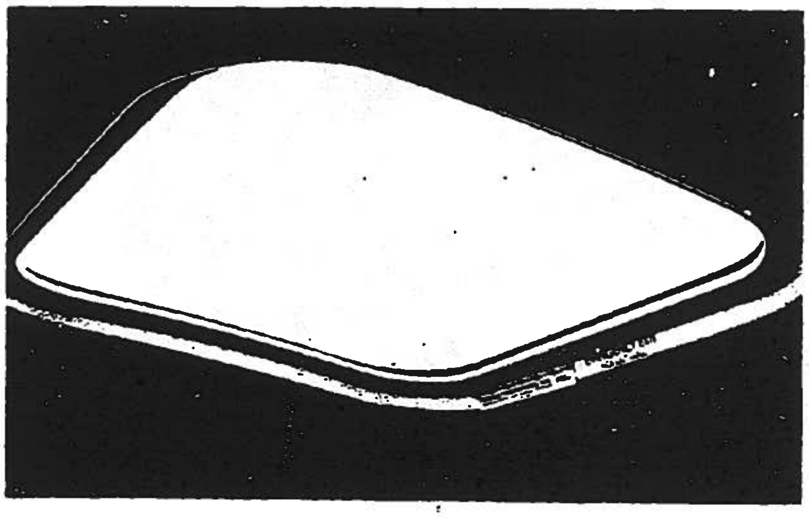

Figure 3.80. View of single roof hatch directly overhead on PD 4905 bus model.

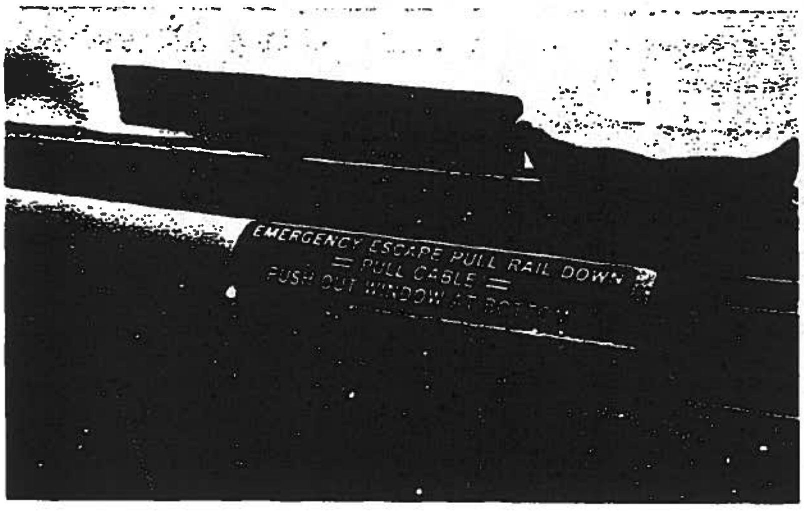

Figure 3.81. Instructions for opening side window of PD 4905 bus model.

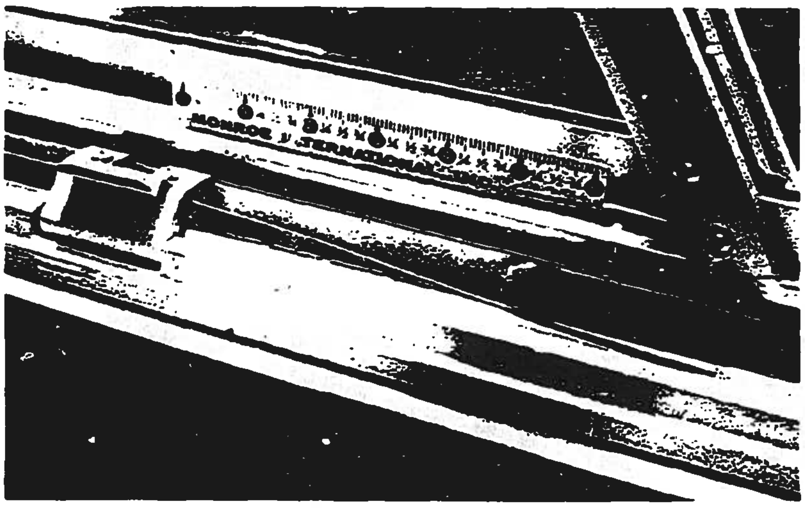

Figure 3.82. View of bus side window with release bar pulled down on PD 4905 bus model.

window area (approximately 23 in by 23 in) which is adequate for escape, but the window will block the exit for the passenger in the next row of seats. The second method of opening the window is simply to push the lower portion of the window out. The window is retained by a metal plunger inserted into a rubber grommet as shown in Figures 3.77 and 3.78. In the bus window retention test program conducted under Contract FH-11-7303 it was found that this type of fastener required a minimum force of at least 100 lb to release the first retainer of the two retainers used on each window. This level of force would be unacceptable under the new maximum force level of 60 lb specified by the Bus Window Retention and Release standard. The window would also not meet the new window retention requirements of the standard. After the window is open, escape would proceed as discussed in Section 3.5.1.1. The drop to the ground when the bus is in an upright position is seven ft.

<u>3.5.1.5 The PD4905 bus model</u>: This bus has a passenger capacity of 49, or 47 when equipped with a lavatory. It has eight windows which can be used as emergency exits, each in a parallelogram shape and each having the dimensions of 69 in by 24 in. The bus meets the window escape area specifications of the new Bus Window Retention and Release standard.

The PD4905 is the only bus of the group analyzed which has a roof hatch for escape when the bus is on its side. There are three roof hatches which are shown in Figure 3.79.

The location of these hatches is as follows: the first hatch is located over the third passenger seat on the left side; the second is located over the sixth passenger seat on the right side; and the third is located over the ninth passenger seat on the left side. Four passenger seats are located between the third roof hatch and the rear window. The hatches are opened by pushing out at the frosted plastic glazing which can be seen clearly in Figure 3.80. The hatches are located off-center of the mid-line of the bus. Discussions with the bus company personnel indicated this was due to structural considerations. The drop which would be required from the lower edge of the roof hatch to the ground would be approximately two or four ft, depending on which hatch the passenger chose to exit.

The side windows of the PD4905 operated on a principle similar to that of the Challenger bus model. However, they could also be opened for ventilation as on the PD4107. If they are opened in this manner, they provide an escape area of approximately 23 in by 23 in, but block the remaining portion of the window for the passengers in the adjacent seat. When the windows are fully released for escape, three distinct operations must be performed. These are: first, pull down the release bar which is located at the lower base of the window; second, pull the secondary release cord which is then exposed; and third, push out the window at the bottom. Instructions are provided on the outside of the release bar as shown in Figure 3.81. Once the release bar is down, the instructions are no longer in sight as shown in Figure 3.82. The release cord is clearly exposed as contrasted with the Challenger design and no sharp window corners are present. The window is hinged at the top and the window may have the tendency to slam shut on a passenger escaping while the bus is in an upright position. The same problem which would occur with this type of hinged window on the earlier models, for example the Silver Eagle, would exist. The drop from the lower edge of the window to the ground is 6 ft, 10 in.

3.5.2 Additional Comments on the Bus Window Retention and Release Standard

Establishment of window retention requirements for intercity buses is a much-needed step and will certainly reduce the number of passengers ejected from a bus during a crash.

The provision of requiring at least 67 sq in of unobstructed emergency exit area per bus passenger seat is not likely to result in any improvement in the number of emergency exits available, since all of the buses analyzed in Section 3.5.1 already meet this requirement. Thus, it can be expected that the times for escaping from the intercity bus as reported in Section 3.3 will not be reduced, and could even be lengthened significantly, if no more area for escape than that required by the standard is provided.

As shown in the testing conducted under Contract FH-11-7303, the requirement that a "rear exit" or "roof exit" be provided should result in a significant reduction of escape time when a bus is on its side. It is suggested that the term "rear exit" be further defined, since an exit door in the side of the bus at the rear would not be suitable as an exit when the bus is on its side. The provision of both a rear-facing exit door at floor level and roof hatches would provide the best arrangement for escape worthiness.

The provisions for labelling emergency exits to clearly indicate how the release mechanism operates should also result in an improvement of escape worthiness. It was demonstrated in Section 3.5.1 that the instructions for operation of side window exits need improvement.

Definite consideration should be given in the standard to requiring that bus windows used for emergency escape remain open after use by the first person escaping. Such a provision is necessary if injuries to escaping passengers due to a large, heavy window falling back on them are to be prevented. It was shown in Section 3.5.1 that windows currently used have sharp objects fixed to the window frame which are a part of the latch used, and also sharp corners, both of which can produce injury. If it is not feasible to require that the window remain open, then sharp objects should be removed from the interior window frame and sharp corners should be rounded.

It has also been demonstrated in the analysis performed in Section 3.5.1 that there is a definite need for compliance with the new requirement that the exit latching mechanism be operable by a single person. There is also the need to require that all latching mechanisms which require two different force applications be clearly labelled, taking into account the position of the latching mechanism at each stage of operation. It is suggested that a latching mechanism requiring only one force application is superior from an escape worthiness viewpoint, since passengers in a panic situation have been shown to operate the first step, but not recognize that a second step is required for two-step latching mechanisms.

Finally, the allowable force levels for operating exit latches should be reduced for the area of high force application, based on data currently becoming available on human strength. Chaffin (15) has developed data on a significantly large sample of adult females which indicates that the maximum lifting force which can be exerted by the 50th percentile female under optimal conditions without injury is 50 lbs, and only 25 lbs for the 5th percentile female. Since the forces exerted for opening an exit will not be produced with the subjects in such an optimal position, it must be questioned whether the 60 lb force allowed by the standard is realistic.

It is also shown in Appendix C.5 that the maximum force which could be produced by a sample of young, healthy females in opening a door latch for a passenger car did not exceed 35 lbs.

In summary, the newly issued standard for Bus Window Retention and Release represents a definite step forward in assuring escape worthiness but further improvements in its provisions should be considered.

3.5.3 Conclusions

The following conclusions are drawn from the research presented in Sections 3.3, 3.4, and 3.5:

1. The use of push-out type school bus windows tested under Contract FH-11-7303 provides a superior means of escape as compared to the split-sash windows tested in this research effort. This superiority is based primarily on their larger size (24 1/2 in by 20 in) as compared to the split-sash window (24 in by 12 in) which allows better entry to the window and exit to the ground level.
2. The force level available from school children of ages 6-11 yr is insufficient to push open the type of push-out window tested under Contract FH-11-7303, and yet such windows are likely to be opened by passenger impact in a crash, resulting in passenger ejection. A positive latching arrangement is therefore necessary if the advantage of push-out windows is to be achieved for emergency escape.
3. The superiority of a rear-facing emergency door exit at bus floor level was again apparent, as it was for the tests conducted under Contract FH-11-7303.
4. Regular escape drills with planned escape exit use could reduce the time for emergency escapes significantly. All bus escape tests demonstrated that exits

are not fully utilized when passengers are allowed to select their own escape strategy.

5. The potential for injury must be considered when designing windows which can serve as escape exits. This injury potential could be reduced by requiring that windows be designed to remain open when pushed open the first time for escape.
6. A requirement that sharp objects be removed from the window frame should be considered to reduce the injury potential of a window falling back upon an escaping passenger.
7. Sufficient data has been developed from the bus escape tests to permit the reasonable prediction of escape time from either a school bus or intercity bus for any of the conditions tested. This prediction could be accomplished as follows:
   a. Establish the number and type of exits to be used for escape, and the conditions of escape from the types of exits tested.
   b. Select the number of passengers which will be used as the bus load for which the escape time is to be predicted.
   c. Perform an iterative procedure of multiplying the number of passengers escaping from each type of exit by the time per passenger escaping, continuing to adjust the number of passengers escaping from each exit until a balance is achieved between the total escape time for each type of exit. This balance will be in terms of a particular exit being the predictor of total escape time, given that the difference between this total escape time and the total escape time for any other exit is less than the comparable difference in escape time which would result if it is

assumed that the number of passengers escaping from any other exit is increased by one.

8. More escape problems will occur when a school bus or intercity bus is on its side, unless suitable roof hatches or a suitable rear-facing emergency exit door are provided. A suitable door means a light-weight or ejectable door.

9. The design of emergency exit operating handles or levers should not exceed the strength capabilities of children for the type of force application used. It is suggested that an increase in selective busing of children in the elementary grades will make this design requirement an increasingly important part of escape exit design, since the entire passenger load will often be small children.

10. Escape exit latching arrangements which require the coordinated action of two persons or more are likely to be unsuitable in any panic escape situation. This fact was demonstrated when the rear window on the school bus could not be opened on the first escape trial, even under near optimal escape conditions in terms of panic.

11. Escape exit latches which utilize a two-step opening procedure are likely to result in operating problems during a panic escape. This problem will be compounded when the cable-release type of latch is used and the cable cannot be easily seen when the release bar is pulled upward, hiding the cable from passenger view.

12. Recent data on female strength capabilities indicate that the force requirements specified in Part 571--Federal Motor Vehicle Safety Standards, Bus Window Retention and Release, are higher than females can produce for the area specified for high force application.

13. The specification of an acceptable escape time from a bus cannot be accomplished without further evaluation of such variables as the flammability of materials and fuel containment in a crash, which were beyond the scope of this contract. However, escape times longer than the 90 sec utilized by the FAA for aircraft escape with 50 percent of the exits usable should be viewed with skepticism. One local school bus collision resulted in an almost instantaneous gasoline fire covering the entire floor.

3.5.4 Recommendations for Further Research and Standards-Making Activity

1. Additional experimental data are needed for establishing size, location, and operation of emergency exits in relation to human preformance capabilities of passengers. Additional data on exit marking and exit operating instructions are also needed.
2. An evaluation of the effects of escape training and instruction on escape performance should be completed. The time required for attaining a given level of proficiency with different training schedules and passenger loads should be documented. Suggestions for such training, if recommended as a result of the studies, should be made in a form which could be widely disseminated.
3. The needs for additional special equipment necessary for escape and rescue, plus first aid and fire control equipment, should be documented for buses. A performance standard should incorporate requirements for these additional items aboard a bus.
4. Further research should be performed to support the following modifications of the Bus Window Retention and Release standard:

    a. Provision that emergency escape windows remain opened when pushed open the first time for an escape.
    b. Provisions for eliminating sharp corners on the window frame and latching mechanism for emergency escape windows.
    c. Provision that all window and door latching mechanisms be operable by only one female possessing strength capabilities no greater than the 50th percentile.

5. Additional experimental data are needed to assess the possible advantages of escape strategy assignment and potential means of reinforcing the assignment (e.g., by color coding seats to exits or by use of arrows, etc.).
6. Additional data is needed to support the issuance of standards stipulating the maximum operating force for emergency exits on school buses.
7. The potential problems of carry-on luggage which is placed in the package rack of buses should be evaluated. These problems include both injury from being struck by such luggage in a collision, as well as the possible obstacles such luggage would pose for escaping passengers.
8. The needs for routine exit maintenance and a daily pre-trip inspection of emergency exits should be documented.
9. Some means of improving access to windows when a bus is on its side should be sought. Any reduction in drop height from any escape route will also be an improvement.
10. With the increase in selective loading of buses by age of children, it is becoming more critical that the driver and adult monitor, if any, not be incapacitated by a collision. This observation suggests both mandatory use of restraint systems and an educational compaign explaining the necessity to the drivers.

11. The advantages of roof escape hatches for school buses appear to be amply demonstrable to warrant their requirement.

12. In any consideration of lap belts for school buses, two factors of importance are (1) with a bus on its side, the child on the top side will be hanging 8 ft from the ground, and (2) buckle release forces may be too high. The bus driver will have the same problem when the bus is on the right side, except that he will have no place like an armrest with which to break his fall.

13. The need for evacuation and first-aid training for hostesses should be carefully considered.

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CHAPTER FOUR

MOTOR VEHICLE FLAMMABILITY AND FIRE SAFETY

This investigation of motor vehicle flammability was initiated under Contract No. FH-11-7303. During this contract four aspects of the motor vehicle fire problem were addressed: flammability characteristics, which covered both ignition and burning rates of materials used in vehicle interiors, nature of fires in vehicle interiors, fuel modification and fire extinguishment. Under the present contract, No. FH-11-7512, work was continued in these four areas; in addition, at the request of the contract managers, more attention than was originally within the scope of the contract had to be diverted to the collection and examination of vehicle fire statistics. Also, by way of a modest though fruitful effort, a limited number of on-site vehicle fires were investigated. Finally, present construction techniques for vehicle fuel systems were documented.

Although a considerable amount of new experimental data was generated under this contract, the principal outcome of these efforts has been the generalized correlation of the flammability data on vehicle interiors which is firmly supported by theoretical considerations. Based on the results from the previous contract, it had been concluded that the OURI ignition test offered promise for reconciling theory with experiments on vehicle interior materials but that none of the other standard flammability or burning rate tests appeared to have any theoretical significance, which merely affirmed a well known--though possibly not generally accepted--premise.

It is emphasized that the flammability studies under this contract, as well as the previous contract, were limited to vehicle fires which originate in the interior of the vehicles. The more serious vehicle fire problem, which starts externally due to the spillage of fuel following a crash, was not within the scope of this effort.

4.1 IGNITION OF INTERIOR MATERIALS

Of all of the various aspects of the fire problem, the ignition phase should be regarded as the most important since without ignition there can be no fire. Furthermore, dating back to the pioneering work of Fons in 1946 (1), when he proposed that fire spread in a fuel bed can be visualized as proceeding by a series of successive ignitions, the fire spread phenomenon has been linked inextricably to the ignition phenomenon even though the connection has been qualitative rather than quantitative. A major hurdle in quantifying predictions of fire spread in wildlands has recently been reported by Rothermel in 1972 (2) although he does not make use of measurements on ignition in his mathematical model.

During the previous contract, No. FH-11-7303, ignition tests were run on a variety of nylon blends, vinyls, sarans and carpets which were obtained from a local automotive upholstery shop. Under this contract ignition measurements were made on vehicle interior materials (original equipment) which were obtained through the courtesy of the Illinois Institute of Technology Research Institute (IITRI) upon the completion of their contract, NHSB No. FH-11-6892 on burning rates (3). Ignition tests could not be run for all of the IITRI materials because in some cases sufficient material was not left to provide ignition samples. Nevertheless, adequate ignition samples were salvaged to encompass most of the vehicle interior components such as the upholstery fabrics, cushioning materials, assemblies of seating components, headliner materials, door panels, quarter panels, insulation and sound deadeners, luggage compartment liners, wheelhousing covers and cargo panels, and miscellaneous interior trim materials.

In addition to the IITRI materials, ignition tests were run on cottons, rayons, acrylics and polyesters since these materials are used frequently in combination with vinyls and nylons as blends for vehicle interior components. Filter paper was also included in the test program for three reasons:

1. A substantial amount of paper derivatives are still used in vehicle interiors, particularly in door, quarter and filler panels, headliners and sound deadeners.
2. Filter paper is readily available in a variety of grades which cover a wide spectrum of properties.
3. Paper constitutes a common reference standard for a qualitative comparison of flammability.

Finally, the replacement interior components for one vehicle, which was investigated thoroughly after its interior was completely gutted by a "real-life" fire, were subjected to ignition tests.

4.1.1 Procedure for Ignition Tests

Since a detailed description of the equipment and techniques for conducting piloted ignition tests was presented in the final report (4) for Contract No. FH-11-7303, it will not be repeated here. Briefly, the ignition test entails exposing the test specimen--in this case the sample is a square 10 cm on each side--to a monitored radiant flux from a benzene flame until the specimen is ignited, or is completely pyrolyzed, or until a sufficiently long exposure to heating has elapsed to indicate that the specimen will neither ignite nor pyrolyze under the test conditions. If the specimen ignites, the observed elapsed time from initial exposure to ignition is recorded as the ignition time. A benzene flame was used as the radiation source since as explained in the previous report (4) the spectral quality of the incident radiation and the spectral absorptance characteristics of the ignition specimen are the predominating variables in the interpretation of ignition measurements.

Based on earlier investigations (5) the benzene flame was judged to be most nearly representative of the spectral emission characteristics of flames from burning vehicle interior materials. Furthermore, with benzene flames, the incident heat flux on the specimen can be varied from the minimum irradiance required to cause ignition in infinite time (ca. 0.5 cal/cm^2-sec) to the highest radiant flux that conceivably would exist in a vehicle interior or exterior fire by simply varying the distance between the sample and the flame.

4.1.2 Ignition Test Results

The piloted ignition times were measured for 83 vehicle interior materials obtained from IITRI. The raw ignition data for each material, which consist of the time to ignition as a function of the incident radiant flux, are reported in graphical form in Appendix D as Figures 1 through 43. The identification numbers of the materials correspond to those used by Goldsmith at IITRI (3); his description of these materials is also reproduced in Appendix D, preceding the figures. Most of the ignition data from these figures is consolidated on the single graph of Figure 4.1 which follows; some of the data have been omitted because of common ignition points. It will be noted that the ignition data fall within a band which covers a spread in ignition times of about one order of magnitude (a factor of 10).

Minimum escape times for occupants from crashed vehicles, who are <u>not</u> injured or trapped, usually cover a range of 10 to 50 seconds. In this time interval practically all of the vehicle interior materials will ignite if exposed to incident fluxes of about 0.5 to 2.5 cal/cm^2-sec. Since these levels of fluxes can be generated by a fire in the vehicle interior, a potential danger to occupants does exist even if they are free to escape.

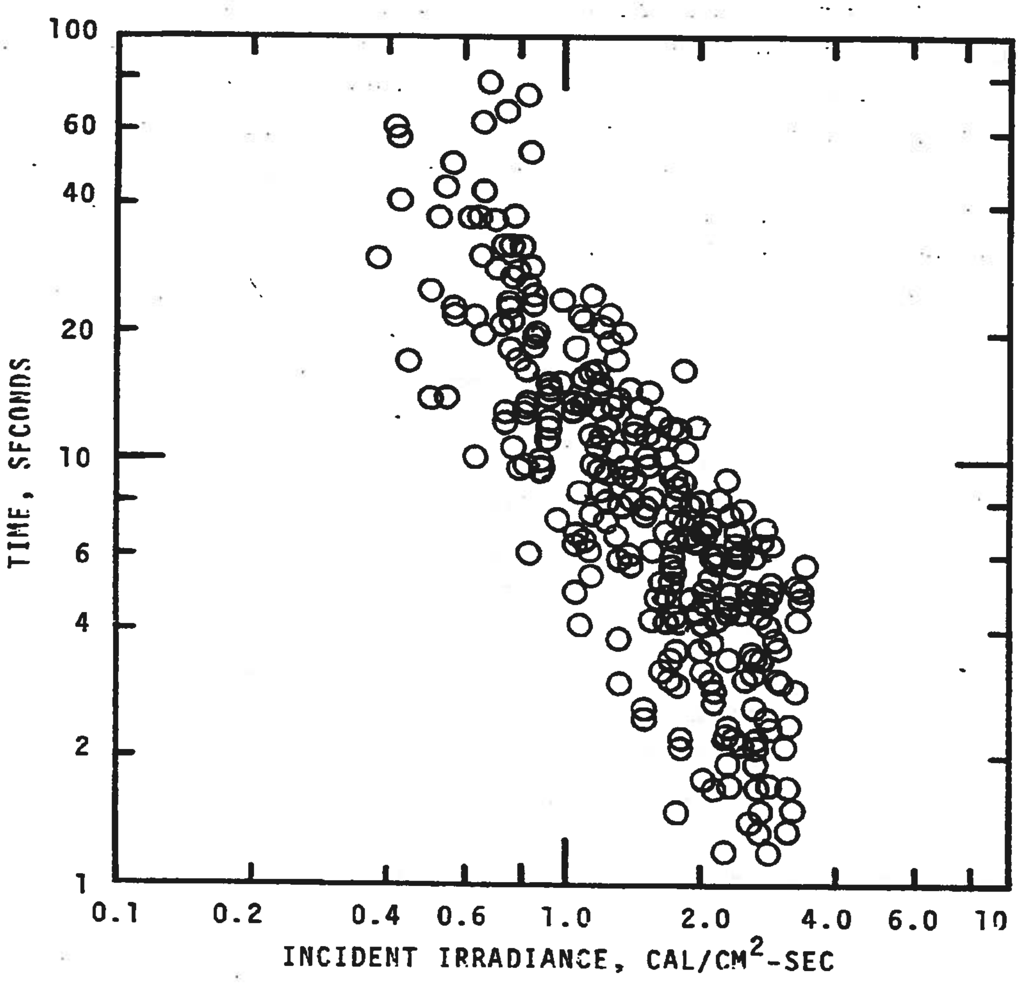


Figure 4.1. Piloted ignition times of IITRI motor vehicle interior materials.

No further reduction of the ignition data on the IITRI materials shown in Figure 4.1 was possible because equipment for measuring the spectral absorptance of these materials was no longer available. During the previous contract, measurements of the spectral absorptance of the vehicle materials obtained locally were made by OURI personnel on government-owned equipment at a private laboratory on the West Coast. About the time that this present contract was initiated, the private laboratory terminated operations. Repeated attempts by the NHTSA Contract Manager to secure this equipment for our use through government surplus property acquisition were unsuccessful. Consequently, the further reduction of the ignition data had to be confined to those materials for which the spectral absorptances had been measured under the previous contract with the exception of carpeting materials. Because of the excessive thickness of the carpet, absorptivities could not be measured in the spectrophotometer-reflectometer equipment which was available.

4.1.3 Correlation of Ignition Data

In the previous report (4), it was shown that the spectral emission characteristics of the flame and the spectral absorptivity of the material were the dominant variables in correlating ignition data. Therefore, the incident irradiance, H_i, has to be converted to an absorbed irradiance, H_a, by

$$H_a = \bar{\alpha} H_i \qquad (4.1)$$

where $\bar{\alpha}$ is the integrated average spectral absorptance of the test material. The results for 14 nylons were then consolidated on a single plot of ignition time versus absorbed irradiance. A similar plot for 12 vinyls was also presented. No further attempts to reduce the spread of the data were made at that time although it was noted that more improvement toward a generalized correlation could be expected according to our previous experience with a variety of woods.

Based on a simplified mathematical model for transient heat conduction through an infinite, solid slab of inert opaque materials, the details of which have been presented before (4, 5), it was concluded that the ignition time, t, can be expressed in the following functional form

$$t = f\,[H_a,\ \rho,\ \mathrm{erf}\,(\frac{\delta}{2\sqrt{\kappa t}})] \qquad (4.2)$$

and more specifically as

$$t = \frac{\lambda\rho^a[\mathrm{erf}\,(\frac{\delta}{2\sqrt{\kappa t}})]^b}{(H_a)^\alpha} = \frac{\lambda\rho^a[\mathrm{erf}\,(\frac{1}{2\sqrt{F}})]^b}{(H_a)^\alpha} \qquad (4.3)$$

where α, a, b and λ are empirical constants

ρ = initial density of the test specimen (gm/cm^3)

δ = thickness of the ignition specimen (cm)

κ = thermal diffusivity (cm^2/sec)

t = ignition time (sec)

F = Fourier modulus = $\kappa t/\delta^2$

H_a = absorbed irradiance (cal/cm^2-sec)

erf = error function (tables of this function are readily available in mathematical references)

The ignition data for each class of materials was then subjected to the correlating form suggested by Equation 4.3. In order to do so, it was necessary to determine the initial density of the materials which for the most part were either woven fabrics or composites containing woven fabrics. The most reliable measurement on the fabric is the weight per unit area, W_o. Then by measuring the thickness, δ, the initial density can be computed by

$$\rho = W_o/\delta \qquad (4.4)$$

Unfortunately, the measurement of thickness of a fabric which is either soft or does not have a smooth surface is of necessity somewhat arbitrary. After much thought, it was decided to adopt the following procedure. The fabric was placed between two hardened discs of steel having a diameter of about one inch and a thickness of about 0.02 inches. Then the total thickness was obtained by conventional micrometer procedures from which the thickness of the two metal discs was subsequently subtracted. This procedure resulted in a slight compression of the fabric; however, by exercising special care the thickness measurement could be reproduced quite consistently by independent observers. In fact, the reproducibility was at least as good as the natural variations in thickness over the test specimen. This technique was something less than satisfactory for the carpet samples since the nap-side was obviously quite compressible even to the slightest force exerted by the micrometer heads, and in some instances the fibers assumed a semi-permanent set. Despite these uncertainties, this procedure was followed, and the results of the thickness and weight measurements, and the calculated densities, are shown in Table 4.1. (NOTE: The designations of humidity or oven-drying in this table apply to the burning rate tests; all ignition tests were run on oven-dried materials.) This listing also includes those materials for which burning rates were measured. In some instances, ignition measurements could not be completed because the specimen melted and dripped off the ignition sample holder before ignition took place. Included in this category are the nylons, N-15 through N-27, and sarans, S-1 and S-2; however, burning rates were obtained for most of these materials.

The results of correlation in accordance with Equation 4.3 are presented in Figure 4.2 through 4.11. The exponents on the density and the error function in the abscissa were obtained through a process of repeated trial and error

TABLE 4.1

FABRIC SAMPLE RESUME SHEET

Sample Number	Description	Thick-ness In.	Mass/Area oz/yd^2	Apparent Density g/cm^3
Vinyls (65% Humidity)				
V-1	Black (Dents)	0.056	29.3	0.69
2	Red (Dents)	051	25.6	67
3	Beige (Dents)	056	28.5	68
4	Beige (Perf)	048	29.8	82
5	Black (Perf)	047	27.4	78
6	Red (Cockle)	030	19.7	88
7	Black	035	23.2	88
8	Beige	023	14.9	85
9	Med. Blue	033	20.7	85
10	Dark Blue	034	22.5	88
11	Metallic Beige	029	17.4	79
12	Light Blue	023	13.8	80
Vinyls (Oven-Dried)				
V-13	Red (Cockle)	0.028	18.9	0.90
14	Gray (Cockle)	018	7.4	55
15	Gray	020	15.8	1.05
Nylons (65% Humidity)				
N-1	Sea Blue	0.031	10.4	0.44
2	Dark Blue	026	9.4	49
3	Beige	034	10.4	41
4	Black	039	11.9	45
5	Gray on Black	040	11.3	38
6	Blue on Blue	036	11.0	41
7	Blue/Green	045	11.9	35
8	Smooth Maroon	024	10.9	60
9	Smooth Light Blue	029	11.6	53
10	Smooth Black	025	10.2	54
11	Smooth Beige	028	12.0	58
12	Smooth Pat. Beige	024	9.9	55
13	Blue W/Metal	047	13.7	39
14	Beige W/Metal	045	13.7	41
15	Light Blue	023	8.5	43
16	Med. Blue	033	7.6	31
17	Dark Mauve	022	7.3	48
18	Light Gray Gold	023	8.5	49

TABLE 4.1--Continued

Sample Number	Description	Thick-ness In.	Mass/Area oz/yd^2	Apparent Density g/cm^3
Nylons (65% Humidity, continued)				
N-19	Charcoal Black	0.022	8.0	0.49
20	Light Gray	022	7.9	47
21	Dark Red	026	7.7	51
22	Dark Tobacco	020	7.8	52
23	Black	021	8.0	51
Nylons (Oven-Dried)				
N-24	Gold on Green	0.033	13.5	0.55
25	Dark Blue Ford LTD #1158, Dealer #1971	027	10.0	49
26	Gold, 1971 Galaxy 500 LTD Base, Dealer #0110	024	7.7	43
27	Medium Blue	020	7.9	53
Sarans (65% Humidity)				
S-1	White/Green/Black	0.010	3.7	0.47
2	Dark Green W/White	010	3.9	50
3	Green W/White	024	6.0	34
4	Black W/White	027	7.9	39
Carpets (65% Humidity)				
C-1	Blue (T-024)	0.155	20.2	0.17
2	Black (T-024)	141	22.0	21
3	Brown (T-024)	135	21.4	23
4	Black (T-009)	174	30.0	21
5	Dark Gold (T-009)	157	30.1	26
6	Dark Ginger (T-001)	133	18.8	19
7	Black (T-001)	125	19.5	21
8	Dark Turquoise (T-009)	155	31.1	27
9	Medium Nugget (T-001)	132	18.2	18
Filter Papers (65% Humidity)				
F-1	Whatman No. 1 (Qualitative)	0.008	2.7	0.44

TABLE 4.1--Continued

Sample Number	Description	Thick-ness In.	Mass/Area oz/yd^2	Apparent Density g/cm^3
Filter Papers (65% Humidity, continued)				
P-2	Whatman No. 3 (Qualitative)	0.015	5.2	0.47
3	Whatman No. 4 (Chemically Prepared)	008	2.7	44
4	Whatman No. 6 (Chemically Prepared)	007	3.0	57
5	Whatman No. 40 (Ashless)	008	2.8	47
6	Whatman No. 54 (Hardened)	007	2.6	49
7	Whatman No. 115 (Wet Strengthened)	004	2.2	74
Heavy Cottons (65% Humidity)				
CT-1	48 x 28	0.026	10.4	0.54
2	48 x 34	022	8.5	52
3	48 x 40	018	7.6	56
4	48 x 44	017	7.1	56
5	48 x 50	016	6.4	55
6	48 x 56	014	6.0	57
7	48 x 60	014	5.7	56
Polyester (Oven-Dried)				
P-1	Lavender Doubleknit	0.005	6.7	0.28
2	Brown Doubleknit	032	6.5	30
Miscellaneous (Oven-Dried)				
	Black cotton	0.006	3.9	0.87
	White Cotton	005	3.9	0.87
	Black Rayon	002	2.0	1.21
	White Acrylic	014	7.5	0.70

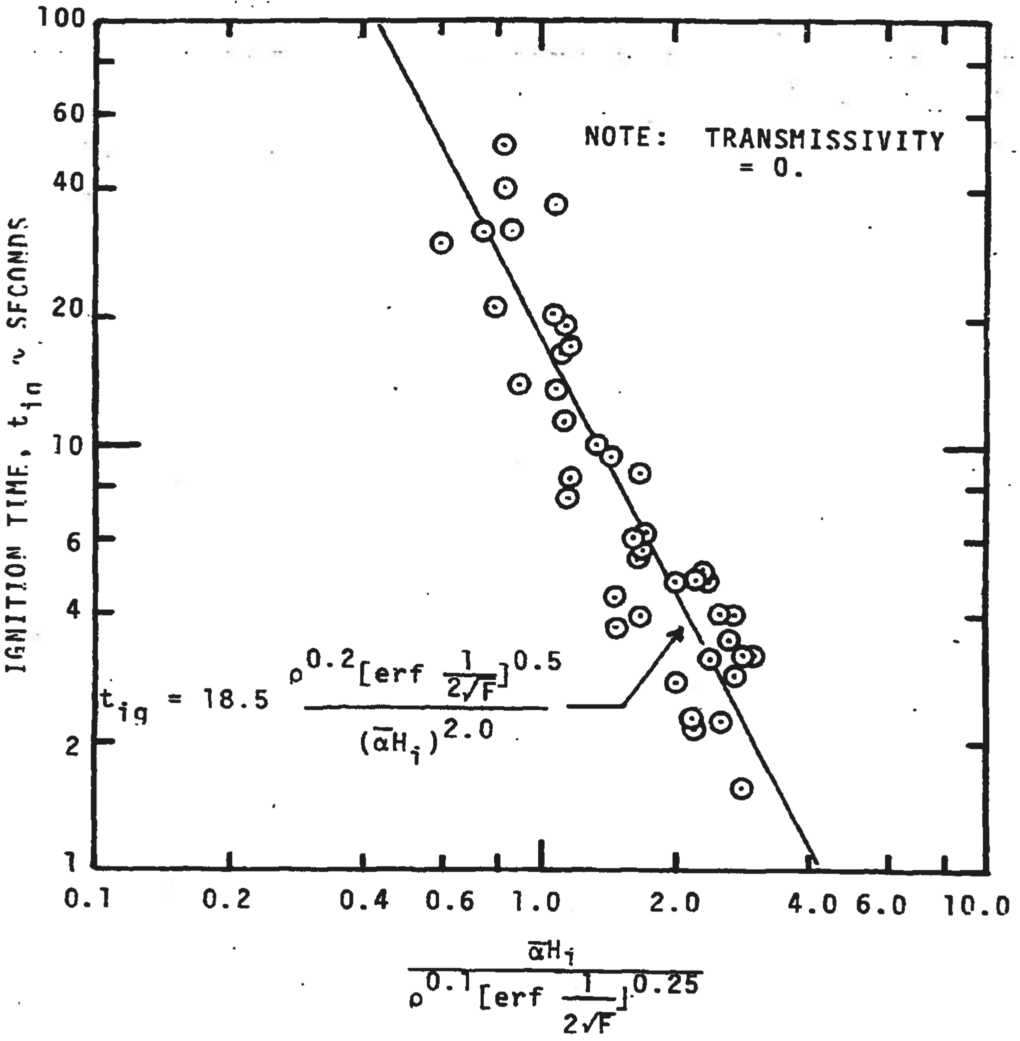


Figure 4.2. Correlation of ignition data for vinyls.

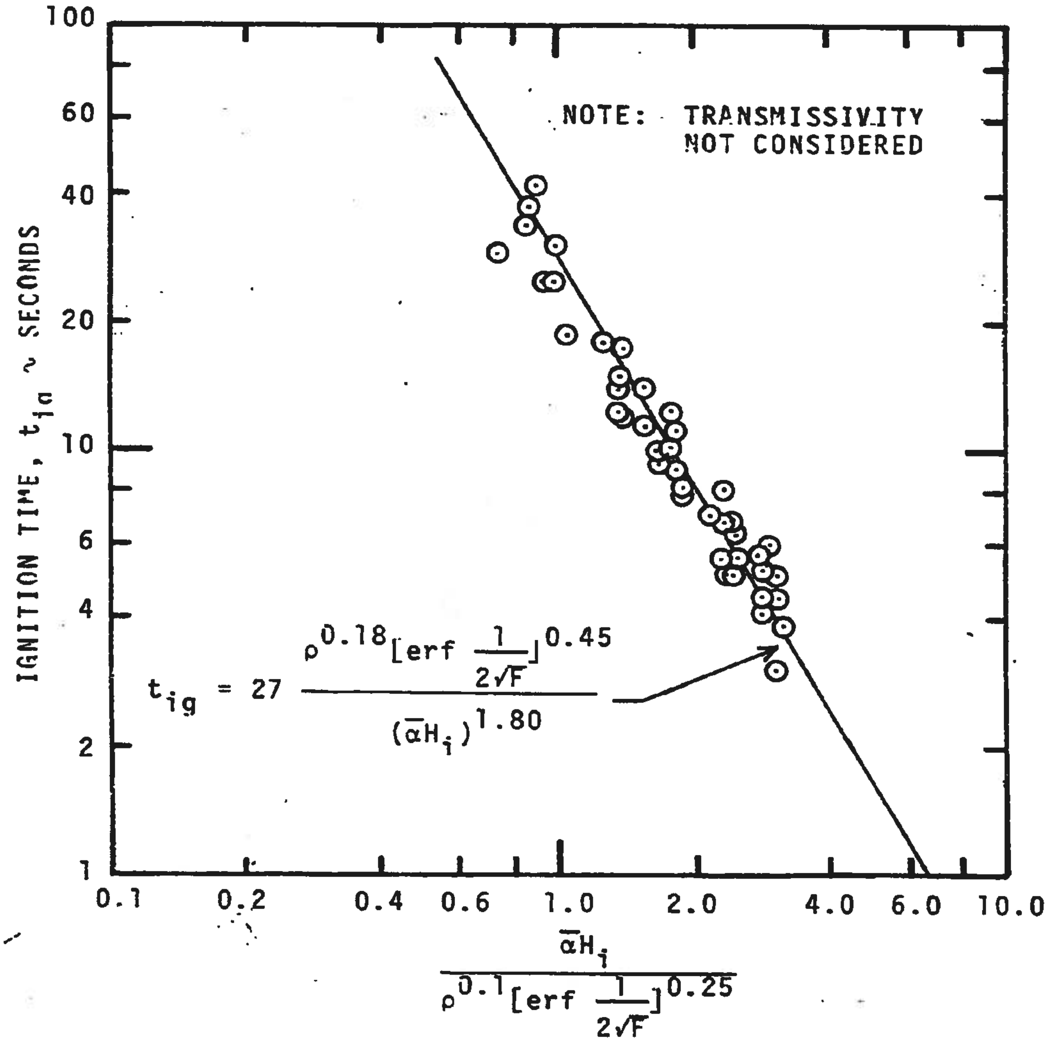


Figure 4.3. Correlation of ignition data for nylons.

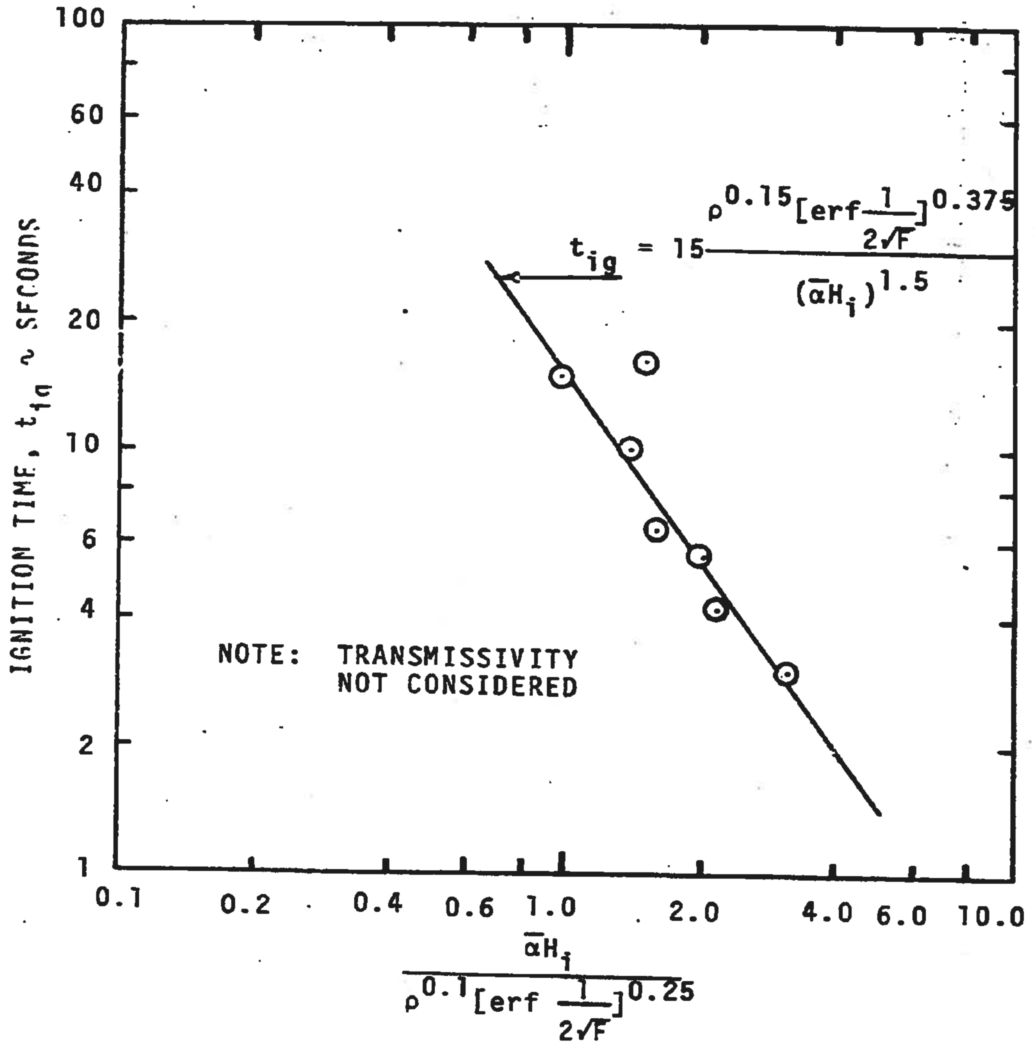


Figure 4.4. Correlation of ignition data for sarans.

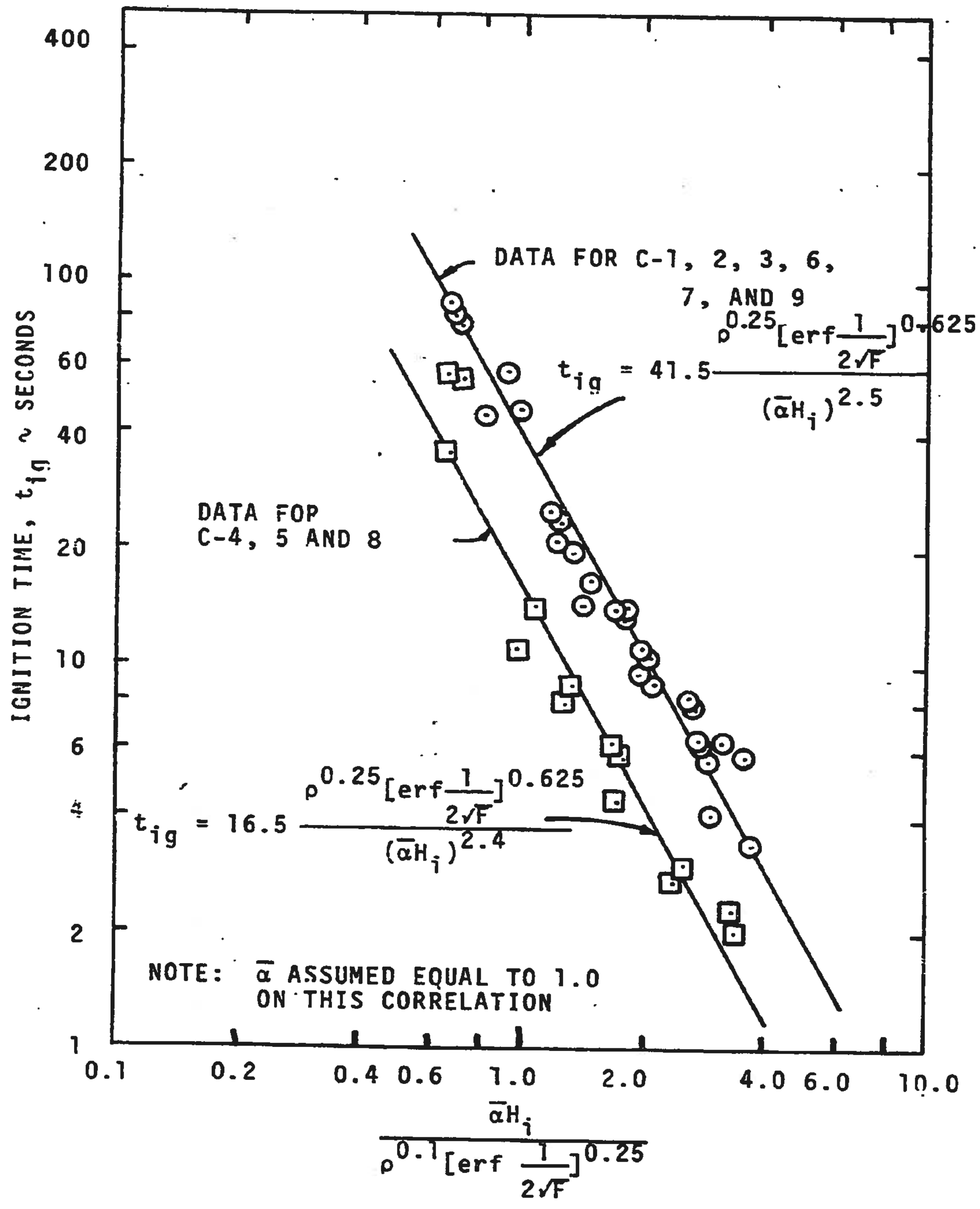


Figure 4.5. Correlation of ignition data for carpets.

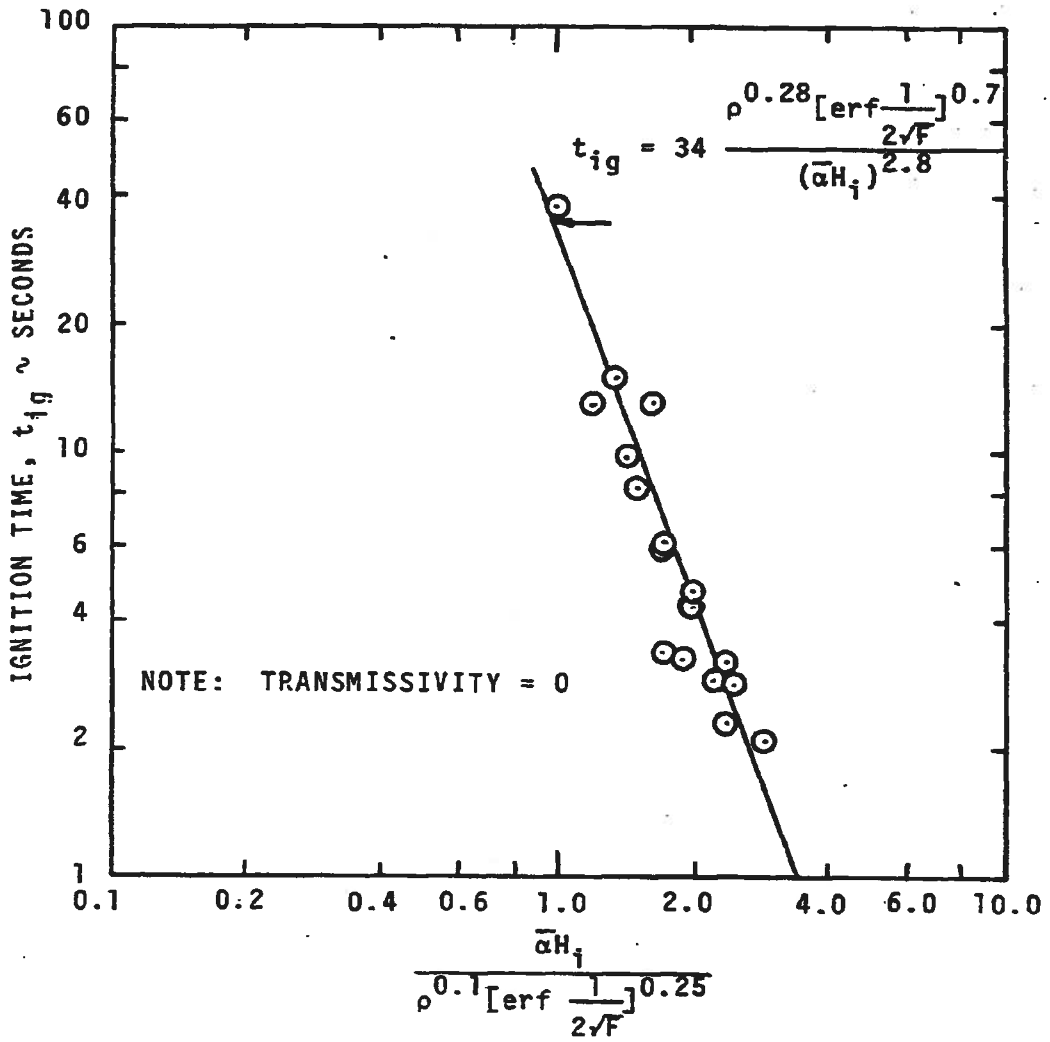


Figure 4.6. Correlation of ignition data for filter paper.

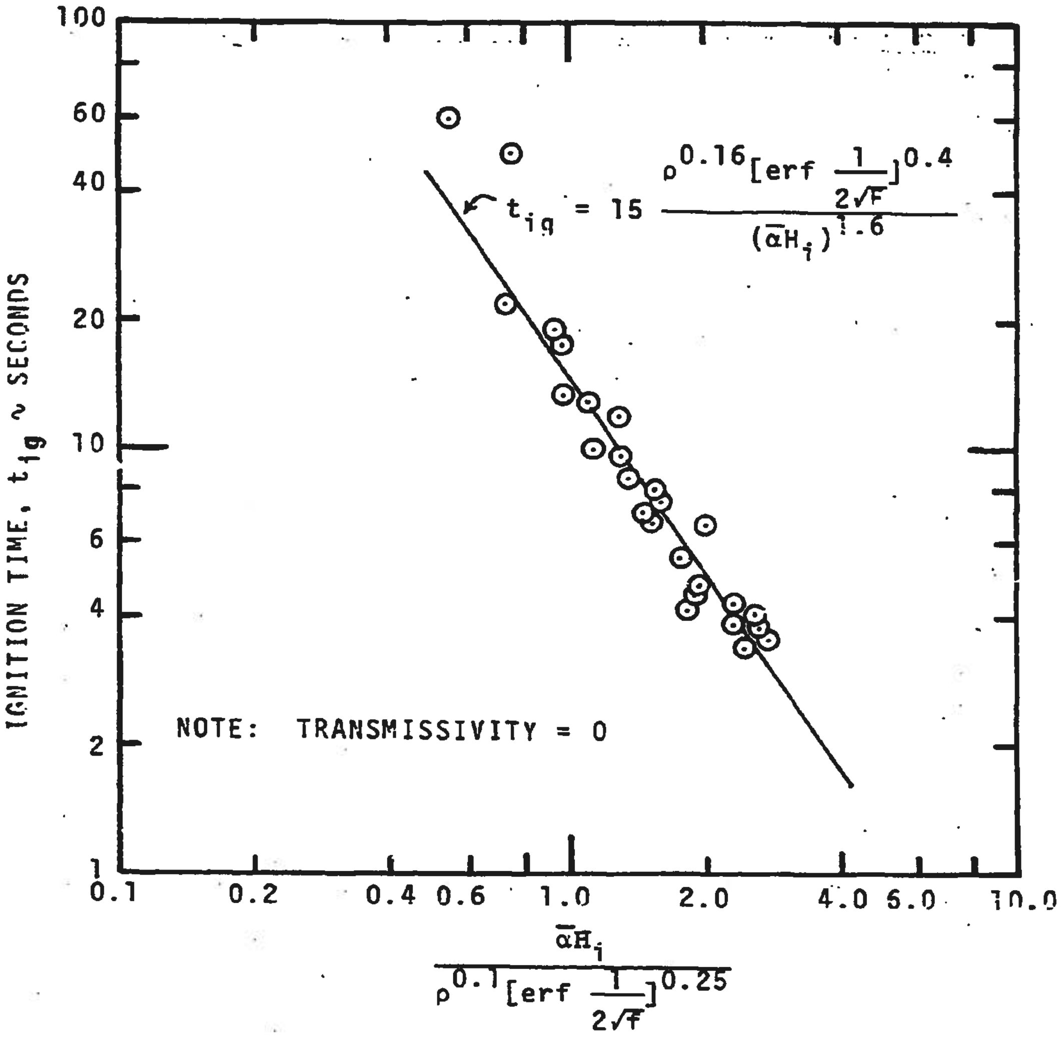


Figure 4.7. Correlation of ignition data for heavy cotton cloths.

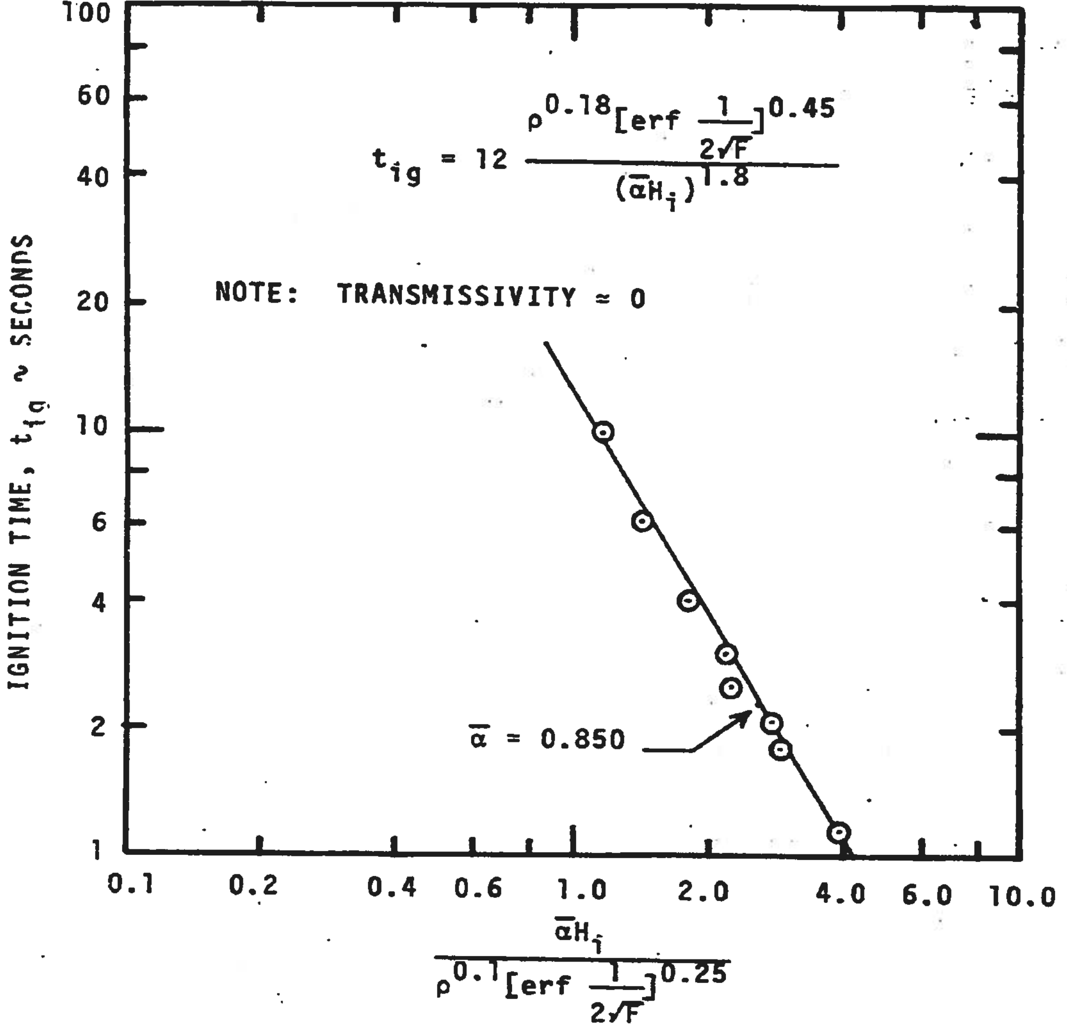


Figure 4.8. Correlation of ignition data for black cotton cloth.

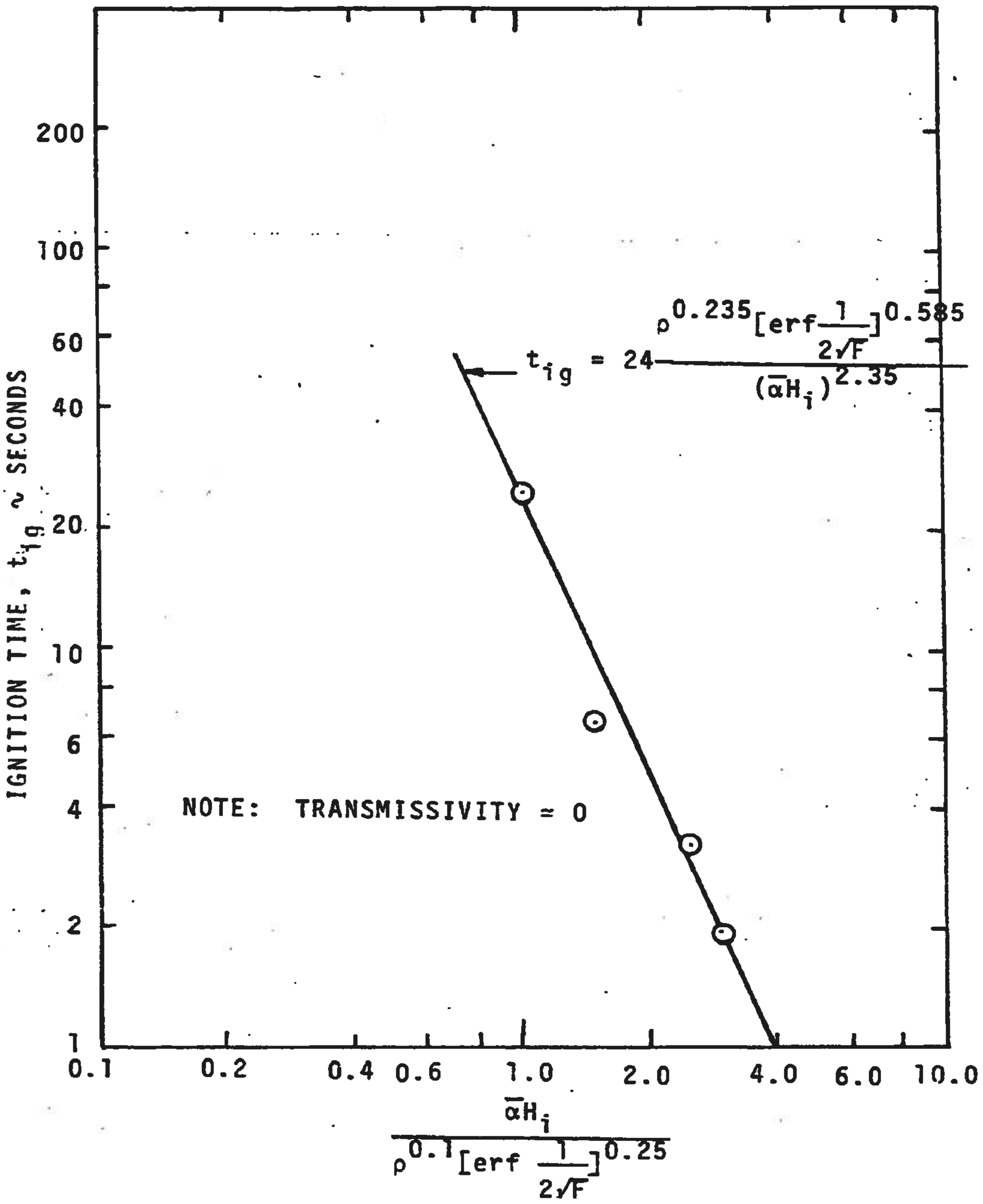


Figure 4.9. Correlation of ignition data for white cotton cloth.

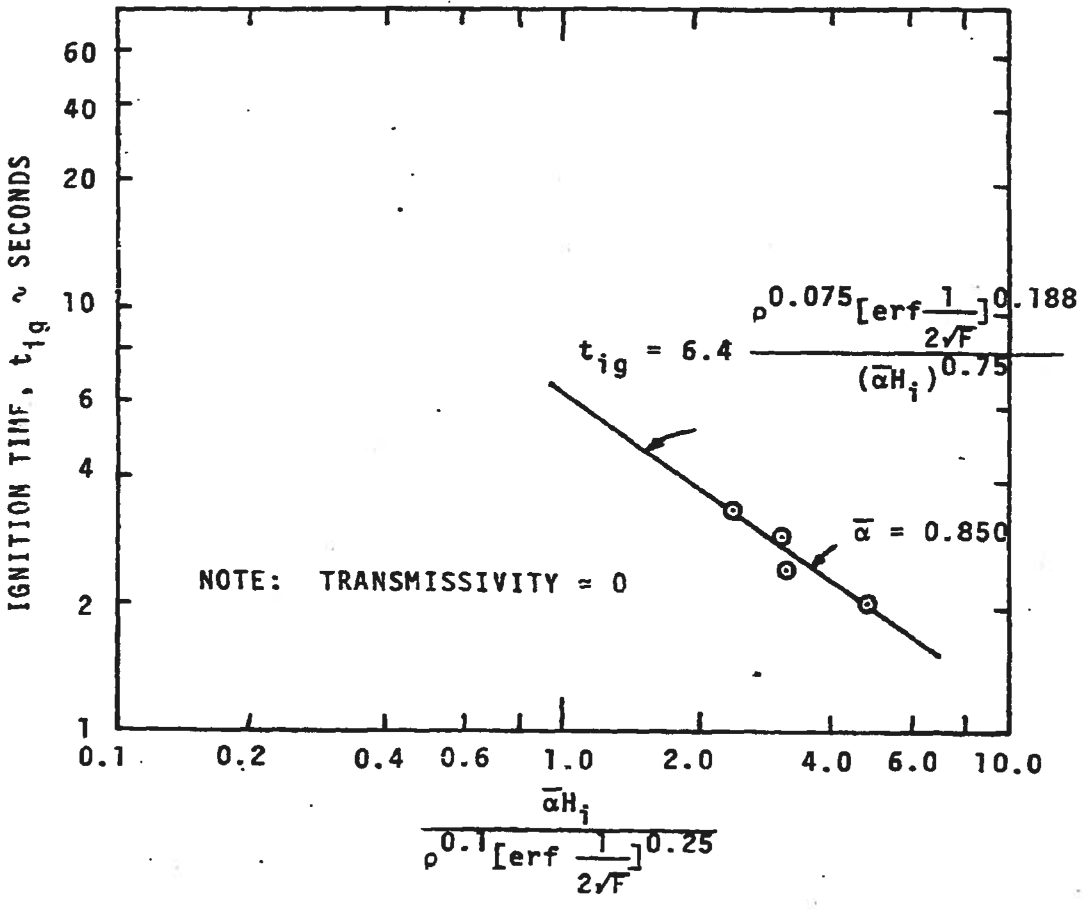


Figure 4.10. Correlation of ignition data for black rayon cloth.

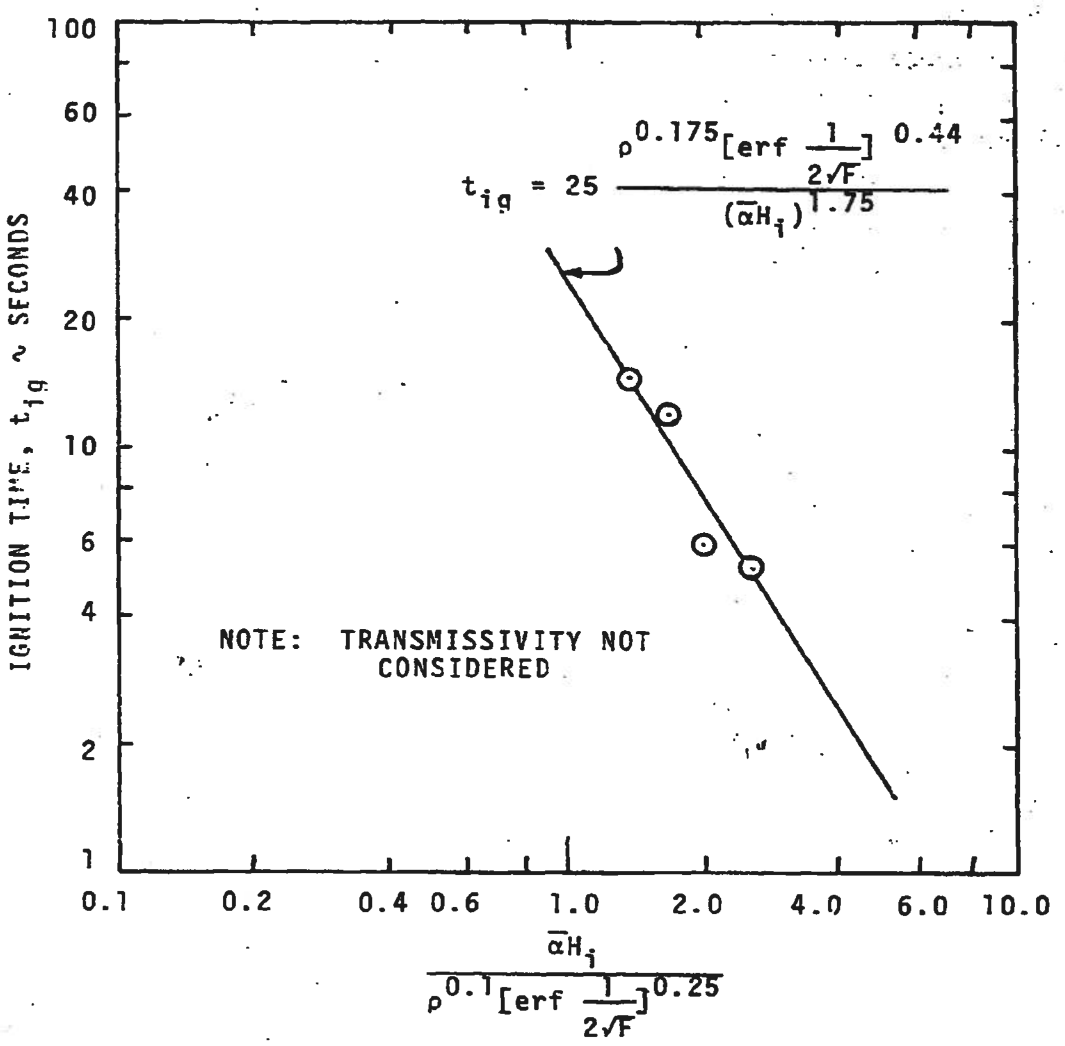


Figure 4.11. Correlation of ignition data for white acrylic cloth.

manipulations of the raw ignition data for all of the materials to determine which exponents gave the most representative fit; these exponents were then used for all materials. As can be seen from these graphs, the correlation is reasonable. The largest scatter is in the data for vinyls, Figure 4.2, and for carpets, Figure 4.5. The fact that the vinyls and carpets have backings of various thicknesses and compositions could account for the scatter.

Average flame absorptivities, as computed from reflectance measurements for all of the materials (except carpets), are summarized in Table 4.2. Note that the variation in absorptivities within a class of materials (e.g., vinyls) is not negligible.

The correlations on the individual classes of materials shown in Figures 4.2 through 4.11 were next consolidated into a generalized correlation for all materials to give Figure 4.12. For the sake of clarity, all data points are not shown; common data points have been omitted. The solid straight line was derived by means of a visual fit. Obviously, a better statistical fit could have been obtained by applying a multiple regression analysis on all of the ignition data. However, this procedure was abandoned since it resulted in an equation which related the variables in a manner that was difficult to reconcile with theoretical expectations. Thus, the <u>visual fit</u> represents a compromise on representing the data for the sake of retaining theoretical significance; it is given by

$$t = \frac{21\,\rho^{0.2}\left[\mathrm{erf}\,\frac{\delta}{2\sqrt{\kappa t}}\right]^{0.5}}{H_a^{2.0}} \tag{4.5}$$

The dashed lines represent the band within which practically all of the ignition data will fall. However, it should be pointed out that a transmittance correction had to be applied to the sarans, nylons and acrylics since these fabrics were open-weave and therefore not opaque. Thus for these materials,

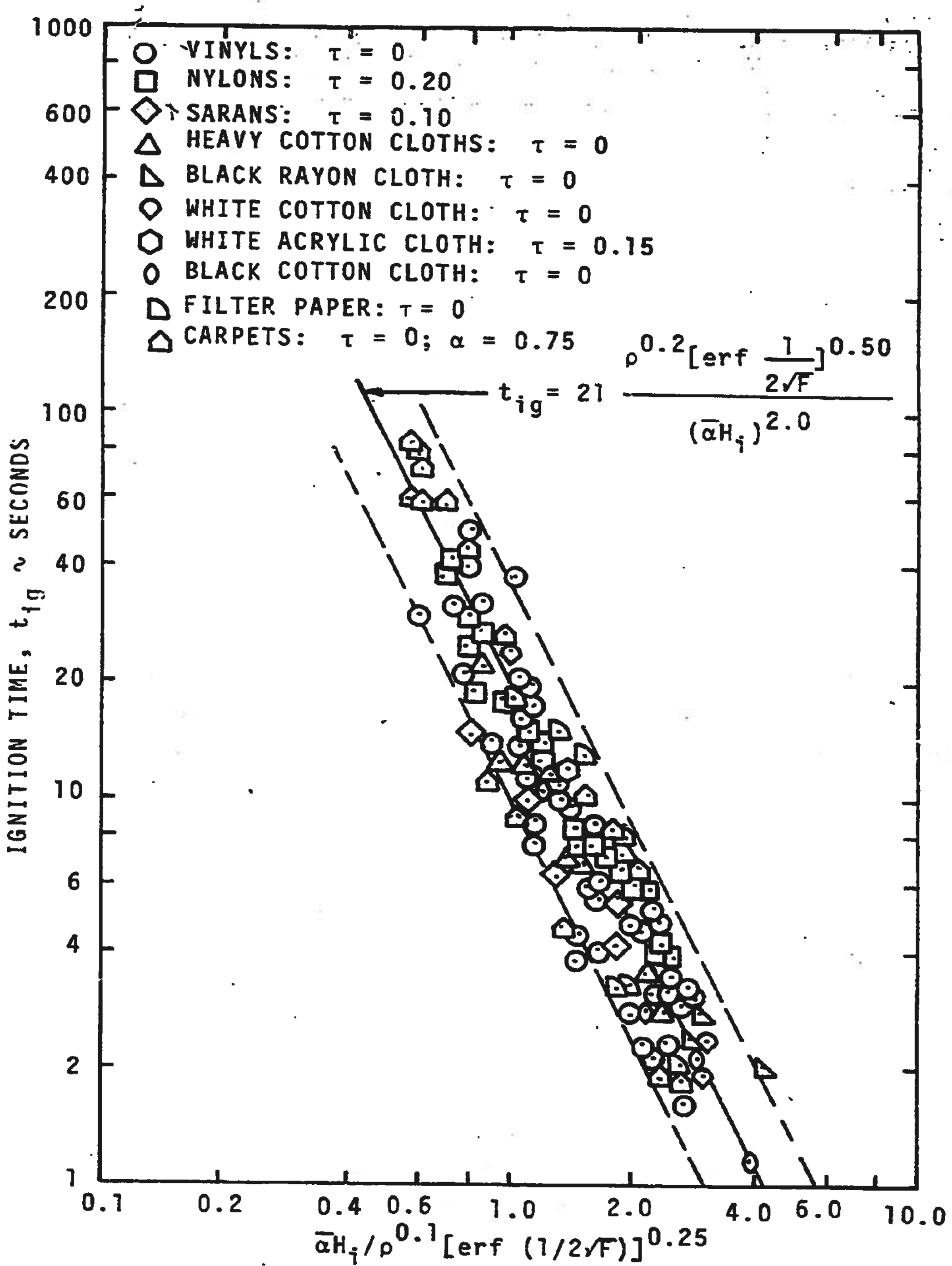


Figure 4.12. Generalized correlation of ignition data for all vehicle interior materials tested.

TABLE 4.2

AVERAGE FRACTIONAL (BLACKBODY = 1.0) ABSORPTANCE FOR FABRICS EXPOSED TO BENZENE FLAMES

Material	$\bar{\alpha}$	Material	$\bar{\alpha}$	Material	$\bar{\alpha}$
Vinyls		Nylons		Filter Papers	
V-1	0.88	N-1	0.77	F-1	0.721
2	81	4	77	2	721
3	81	5	81	3	721
4	78	7	82	4	721
5	89	8	78	5	721
6	78	9	77	6	721
7	88	10	78	7	721
8	78	11	77		
9	78	12	77	Miscellaneous	
10	82	13	78		
11	78	14	77	Black cotton	0.850
12	78			White cotton	721
13	81	Heavy Cottons		Black rayon	850
15	81			White acrylic	721
		CT-1	0.721		
Sarans		2	721		
		3	721		
S-3	0.79	5	721		
4	83	6	721		
		7	721		

Equation 4.1 had to be modified according to

$$H_a = (1 - \bar{\tau})\,\bar{\alpha}\,H_i \qquad (4.6)$$

where $\bar{\tau}$ is the average transmittance. A rough estimate of the magnitude of this transmittance term was obtained by shining a flashlight through the fabric and projecting it on a screen. By counting the number of holes and measuring their size, it was possible to arrive at the following average transmittance factors: Nylons = 0.20; acrylics = 0.15; sarans = 0.10. For all other materials, the transmittance was assumed to be equal to zero. Also, for the carpets, which are primarily nylon blends, an average absorptivity of 0.75 was assumed.

One other point regarding the ignition tests merits attention. Since most of the vinyl materials have a woven fabric backing--frequently cotton--ignition tests were run on three of the vinyls (V-13, V-14 and V-15) first with the vinyl side exposed to the irradiation and subsequently with the cotton backing exposed. In the case of V-13 and V-15, the ignition data for the vinyl exposed and the backing exposed were identical which indicated that the vinyl material controlled the ignition. For V-14, the ignition data for the vinyl exposed was typical of the vinyls whereas the ignition data for the backing exposed was very similar to the longer ignition times for cotton. Thus, for V-14, its ignition characteristics depend upon which side is exposed to heating. The difference in behavior between V-13 (or V-15) and V-14 is attributed to the fact that the V-14 composite had a very thin layer of vinyl as compared to the thick cotton backing. The backing was carefully separated (a laborious task) from the vinyl and the following measurements were made:

Material	Composite	Vinyl Only	Backing Only (by difference)
		Thickness in Inches	
V-13	0.028	0.019	0.011
V-14	0.019	0.006	0.013
V-15	0.021	0.011	0.010
		Weight in gm/cm^2	
V-13	0.0669	0.0453	0.0216
V-14	0.0283	0.0145	0.0138
V-15	0.0552	0.0262	0.0290

Equation 4.5 is certainly adequate for most engineering estimates over the range of ignition times covered by the experimental measurements, namely 2 to 60 seconds. The principal virtue in this generalized correlation is that it does provide the basis for estimating ignition times for a wide

variety of thin materials if no ignition data on the individual materials are available. Extrapolation beyond these limits should be avoided since for ignition times longer than 60 seconds the straight line will become curved upward and will approach a minimum critical irradiance below which no ignition will occur even for infinite exposure times. Likewise, on the lower end of the ignition time spectrum (ca. below one or two seconds), extension of the ignition curve will show a diminishing absolute value for the slope as zero time is approached (6). Nevertheless, the generalized correlation as given by Equation 4.5 is preferred over one or two isolated measurements of ignition times on a given material since the equation smooths out inconsistencies in the experimental data. As will be demonstrated later in the section on burning rate correlations, Equation 4.5 is quite reasonable.

4.1.4 Application of Ignition Results

All of the ignition data presented herein are for piloted ignitions. In other words, the sample was irradiated by an open benzene flame located at some finite distance away (2 to 15 inches). However, a pilot light was located immediately above the front face of the sample. Two types of pilot lights were used during the ignition tests. One was a coil or wire which was heated electrically to bright red heat, and the other was a small tube perforated with tiny holes to constitute a propane gas burner. Thus, as the sample was heated by the benzene flames and combustible gases were released from the sample due to vaporization and/or pyrolysis, the pilot light served as a localized ignition source. For this reason, these tests are called piloted ignition. Without the pilot light, the sample would have to be irradiated for a longer time (perhaps 50 percent or more) or the level of irradiance would have to be increased in order to accomplish self-ignition. Another version of the ignition test is the so-called two-sided ignition which consists of irradiating both faces of the sample simultaneously. Again these tests can be conducted with or without the use of the pilot light. In this case, the ignition times will be approximately one-half of the one-sided ignition (7).

All of these versions of ignition may be involved at some stage in the spread of fire through the interior of the vehicle. For the case of self- or pilotless ignition, the time required for ignition to occur would obviously be longer than Equation 4.5 would predict. Nevertheless, in view of the multitude of circumstances that could lead to the start of a fire in the interior of a vehicle, the use of Equation 4.5 to predict ignition potentials seems prudent.

On the other hand, the ignition data compiled herein are quite useful in predicting potential thermal damage to the skin of vehicle occupants. Figure 4.13 shows a comparison of the <u>incident</u> energy required to produce ignition in vehicle interior materials and that required to effect burns on human skin. The limit for unbearable pain is based on the data of Buettner (8) and for production of blisters on the data of Stoll and Greene (9). It is evident from this figure that the time required to ignite the interior materials at a given level of irradiance is substantially longer than the time required to produce full blisters or unbearable pain. This disparity in time is even more pronounced if the start of the fire is without benefit of a pilot since longer heating or exposure times are involved. Considering the fact that a localized gasoline-fed fire can reach a flux level of about 3 cal/cm^2-sec in a matter of a few seconds, vehicle occupants who are unable to escape due to circumstances beyond their control would become fatalities long before many of the vehicle interior components ignited.

A better idea about the cause, nature and consequences of vehicle fires can be obtained by consulting Appendix B which contains nine in-depth case studies and three special reports on vehicle fires.

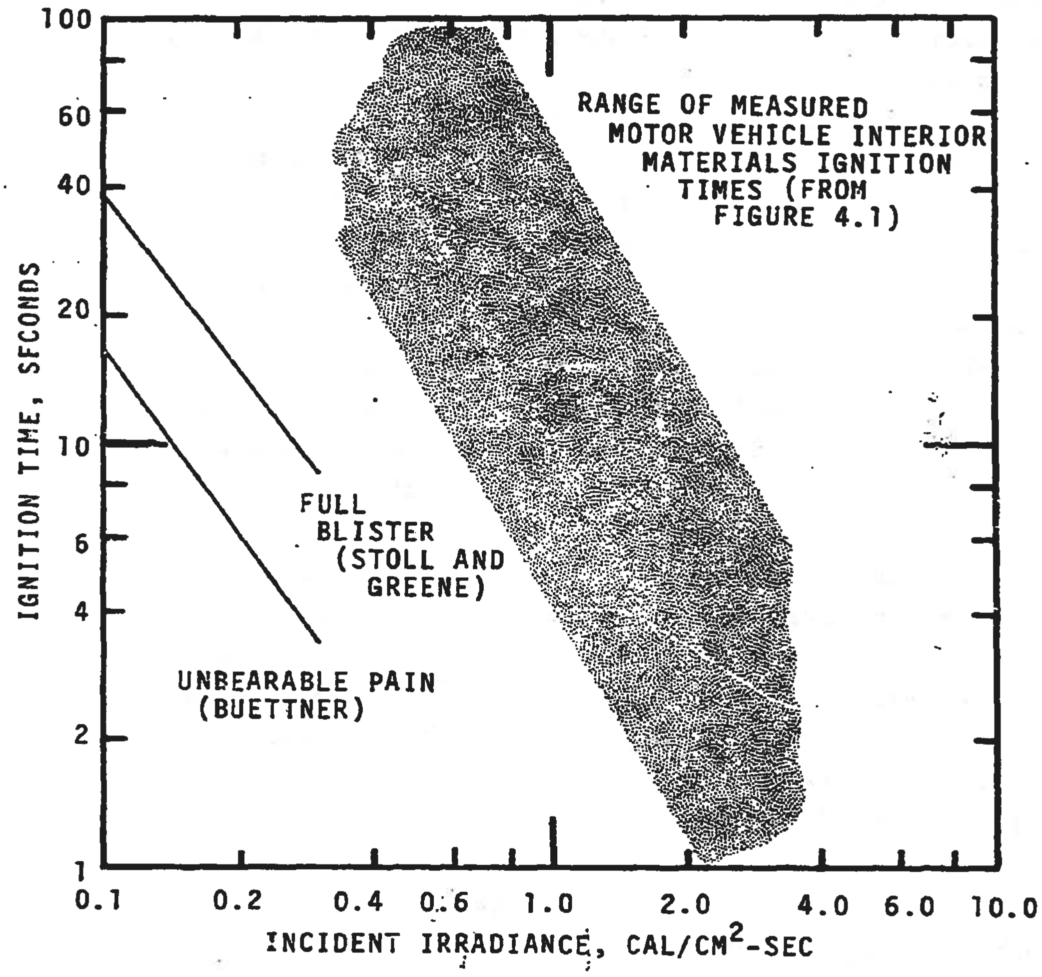


Figure 4.13. Comparison of ignition time for IITRI motor vehicle materials and damage time for human skin.

4.1.5 Conclusions and Recommendations

Based on these continuing studies with the OURI ignition test, which were initiated under Contract No. FH-11-7303, the following conclusions are drawn:

1. Because of its sound theoretical foundation, the OURI ignition test is an important--if not the most important tool--in assessing the flammability of vehicle interior materials. For this reason it should not be altered or compromised in an attempt to obtain direct measurements on flame spread rates simultaneously.
2. Despite the large disparities in physical and chemical properties of vehicle interior materials, the ignition time at any level of flame irradiance between 0.5 and 3 cal/cm^2-sec can be predicted quite satisfactorily for a wide range of natural and synthetic materials if the density, thickness, average absorptivity and transmissivity of the material is specified. If the absorptivity and transmissivity are not known, estimates of the ignition times which are probably adequate for many engineering applications can still be made by means of the generalized correlation developed herein.
3. The materials used in the interior of current vehicles are more resistant to ignition than the human skin is to thermal--and possibly fatal--damage from the same levels of <u>incident</u> irradiance. Therefore, the situation in which a vehicle occupant is unable to escape from a vehicle during the initial stages of a vehicle interior fire is of more concern from the standpoint of severe or even fatal burns than the flammability characteristics of the vehicle materials per se. This conclusion must be tempered to the extent that the possible release of noxious gases during the early stages of heating of the vehicle interior materials has not been delineated.

4. Based on very limited ignition tests (3 vinyls with cotton backing) it appears that the ignition characteristics of the composite material will in <u>some</u> <u>instances</u> be identical regardless of which face is exposed to the radiation flux whereas in other instances the ignition characteristics are dependent upon which face is exposed to the flux.
5. The results of these ignition studies are applicable to thin materials in general, and fabrics in particular, whether they constitute interior vehicle components or not.

Although the OURI ignition test has been validated as a reliable and applicable flammability index for vehicle interior materials, it is recommended that:

1. Additional ignition tests be run in which the sample is heated on one face without a pilot light being present in order to obtain self-ignition times.
2. Additional ignition tests be run in which the sample is heated simultaneously on both faces, both with and without a pilot light.
3. A more reliable technique for measuring the thickness or bulk density of vehicle interior components be developed.
4. More data be obtained on the ignition characteristics of composite materials.
5. More absorptivity and transmissivity data be obtained on fabrics.
6. The spectral emission of flames from burning vehicle interior materials be measured.
7. An ignition cabinet be designed that permits mounting the ignition specimen in a horizontal pan which can contain those materials that melt before ignition occurs. In this case, the radiant source would be a tungsten lamp or radiant panel rather than a flame; subsequently, these data could then be converted to equivalent flame irradiation through the use of average spectral absorptivities.

4.2 BURNING RATES OF INTERIOR MATERIALS

Under the previous contract, No. FH-11-7303, several types of standard burning rate tests were evaluated by running tests on a representative group of vehicle interior materials (4). Use was made of the facilities at the Federal Aviation Administration in Atlantic City, New Jersey (NAFEC) to run the horizontal burning rate test (SAE J369), the vertical burning test (Federal Specification CCC-T-191b, Methods 5902 and 5903T) and the radiant panel test (ASTM-E 162-67). It was concluded from these results that the vertical burning rate test was too severe and that the radiant panel test was too erratic and not sufficiently discriminatory to be of practical value for screening the flammability of vehicle interior materials. On the other hand, the horizontal burning test was concluded to be rather mild based on the premise that the flammability of vehicle interiors could be regarded as a serious problem that needed rectification. Of the 237 vehicle interior materials for 1968 models that were tested at IITRI (3) 80 percent had a burning rate of less than 4 inches/minute. Among this group it was possible to find a combination of materials for outfitting a complete vehicle interior (with the exception of convertible tops and hardtop covers) that had a burning rate of less than 1.0 inch/minute (4).

It is to be noted that the IITRI tests were run in a standard laboratory hood which corresponds to the dimensions of the originally proposed FMVSS 302 (10). This larger test chamber tends to give lower burning rates than the smaller chamber corresponding to SAE J369 (4). Subsequently the National Highway Traffic Safety Administration adopted a standard for horizontal burning rate measurements as FMVSS 302 which is similar in dimensions to SAE J369 (11). Although this new standard for FMVSS 302 was expected to show higher burning rates than the proposed standard, the difference is hardly statistically significant. For example, Table 4.3 summarizes the results of conducting 20 repetitive horizontal burning rate tests each according to the proposed (large cabinet) and adopted (small cabinet) standard with heavy cotton (CT-2 in Table 4.1) oriented so that burning occurred parallel to the warp. It can be seen that although the average burning rate obtained from the adopted standard was 6 percent higher (4.12 versus 3.89 inches/minute) and the percent deviation from the mean was half as much (3.6 versus 7.7 percent) as for the proposed standard, this difference is not very significant since one can be only 38 percent confident that repeated tests will not overlap.

Following the adoption of FMVSS 302 a number of questions were raised from the automotive industry regarding the reliability and merit of this test method for assessing the flammability of vehicle interior materials. Consequently, the emphasis under this contract, No. FH-11-7512, was directed more toward evaluating the test method rather than simply compiling an exhaustive catalog of burning rates for specific vehicle materials which could become outdated within a matter of a few years.

In this section principal attention is given to:

1. The effect of the chemical composition of the material on the horizontal burning rate.
2. The effect of the orientation of the fibers and the surface finish of the materials on horizontal burning rate.
3. The effect of the angle of inclination of the test specimen on the burning rate.
4. The effect of the test conditions and procedures on the horizontal burning rate.
5. The development of a mathematical model for predicting burning rates.

TABLE 4.3

COMPARISON OF THE BURNING RATES OF HEAVY COTTON ACCORDING TO THE PROPOSED AND ADOPTED FMVSS 302 STANDARD (Ambient Test Conditions)

Proposed (Large Cabinet)		Adopted (Small Cabinet)
3.70 inches/minute		4.09 inches/minute
3.75		3.89
3.94		4.18
4.33		4.30
3.30		3.97
4.21		4.39
3.70		4.28
3.59		4.17
3.77		3.81
3.51		3.93
3.75		4.45
4.00		4.05
3.58		3.80
3.88		4.64
4.49		3.96
3.79		3.92
4.35		4.18
4.19		3.99
4.10		4.14
3.94		4.25
3.89	-- Average --	4.12
0.30	-- Standard Deviation --	0.15
7.7	-- Percent Deviation --	3.6

4.2.1 Test Procedures

Although numerous horizontal burning rate test procedures have been practiced in the past, they all have the common objective to measure the rate at which the flame propagates along the plane of the test specimen after it is ignited on one end. As will be discussed later, the absolute value of the measured burning rate is more dependent on the test procedure than on the properties of the test specimen itself.

Burning rate tests under this contract were confined almost entirely to the procedures specified by FMVSS 302. Two apparatuses were involved.

The smaller version of the horizontal burning rate apparatus at OURI was constructed to the specifications of FMVSS 302 (11). Basically, it consists of a small cabinet, 8 inches by 15 inches by 14 inches high, with provisions for ventilation at the bottom and top. Figure 4.14 shows the cabinet. A sample holder is formed by a clamp 4 inches wide and 14 inches long (Figure 4.15). The sample is also 4 inches wide and 14 inches long (Figure 4.16), and the maximum allowed thickness is 1/2 inches. It is conditioned at 70 ± 2°F and 50 ± 5 percent relative humidity. It is placed in the sample holder which is then positioned in a frame in the cabinet. The sample is ignited at one end by the flame from a Bunsen burner (Figure 4.17). Any gas which has a flame temperature equivalent to natural gas can be used as a fuel. The burner flame is 1-1/2 inches high. It is placed underneath the free end of the sample, which stands 3/4 inch above the burner, and is held there for 15 seconds and then removed. Flame contact is made 1-1/2 inches from the first of two marks 10 inches apart. If the material continues to burn, the time required for the flame to propagate between the two marks (Figure 4.18) is measured, and the burning rate in inches/minute is calculated. If the flame propagates only part way between the two marks, the material is classified as self-extinguishing; in this case the burning rate is based on the distance burned as measured from the first mark and the time to extinction. If the flame does not propagate to the first mark, no burning rate is reported. If the material does not ignite during the 15-second exposure, it is reported as nonigniting.

An earlier version of the burning rate test equipment is based on the Notice of Proposed Rule Making for FMVSS 302 (10). This apparatus differs from the adopted standard only

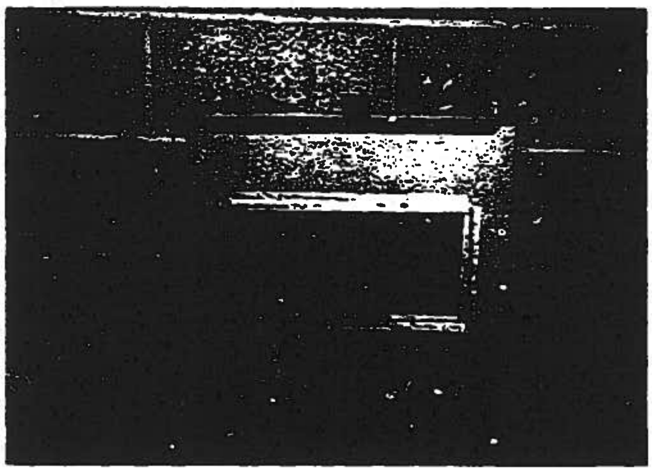


Figure 4.14. FMVSS 302 horizontal burning test apparatus (small cabinet).

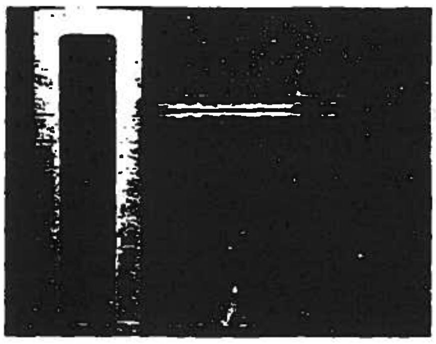


Figure 4.15. Sample holder and U-shaped clamp.

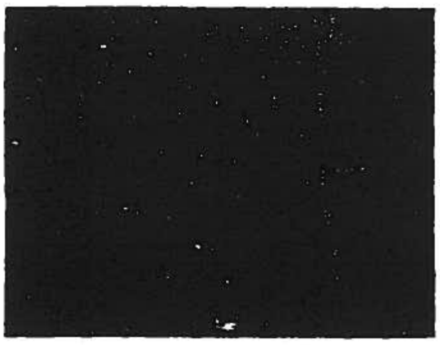
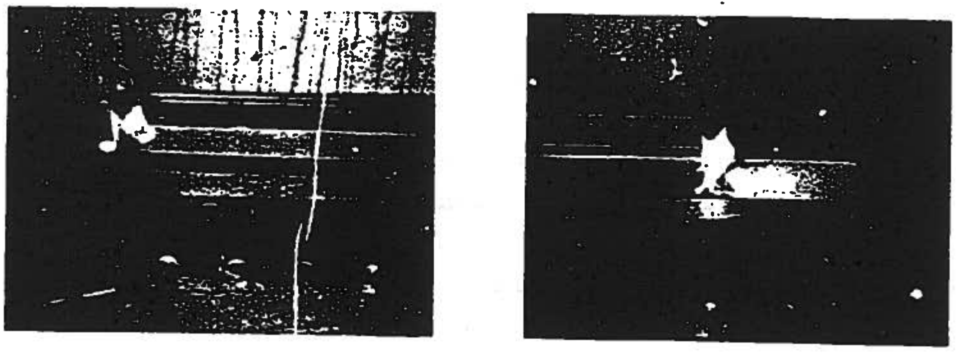


Figure 4.16. Sample of red vinyl showing backing.



a.

b.

Figure 4.17. Burning test in progress.
a. Beginning of test.
b. Nearing completion of test.

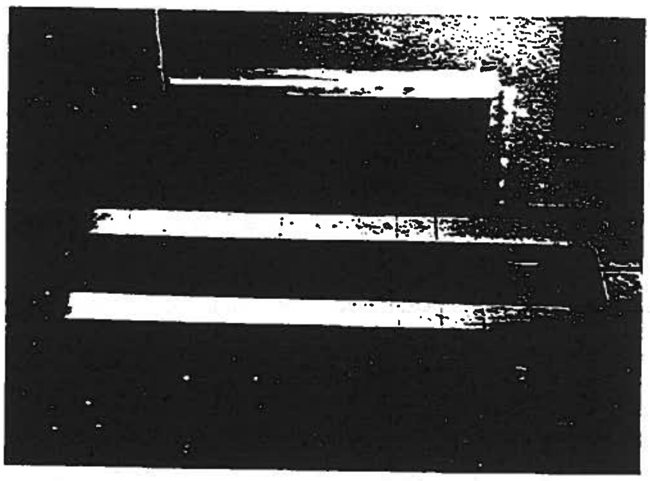


Figure 4.18. U-shaped clamp with indicating marks.

in that the size of the enclosure is much larger; it is 45 inches wide, 20 inches deep, and 41 inches high with a full front window as shown in Figure 4.19. Combustion gases exhaust through a 3-3/4 inch round opening in the center of the roof; and fresh air enters through a rectangular 3-inch opening that extends all the way across the bottom of the front. The ambient air is defined as 70°F and 65 percent relative humidity.

The sample is a rectangle 4 inches by 14 inches and a maximum of 1/2 inch thick. It is held by a set of U-shaped clamps which fit into a holder similar to that shown in Figure 4.15. For the inclined burning test the clamp and holder are mounted in a rack that provides for adjustment of the angle (Figure 4.20). If the sample cannot support itself between the clamps, 5 mil Chromel wires spaced at 1-inch intervals can be used. The sample is ignited at one end by exposing it to the flame from a Bunsen burner for 15 seconds. The gas specified for fueling the burner (Matheson "B" Gas) is 55 ± 1 percent hydrogen, 24 ± 1 percent methane, 18 ± 1 percent carbon monoxide and 3 ± 1 percent ethane; the flame from the 3/8-inch inside diameter burner tube is specified to be 1-1/2 inches long. The sample is conditioned for 24 hours at 70°F and 65 percent relative humidity.

Approximately 2000 burning rate tests were run on vinyl (V), nylon (N), saran (S), cotton (CT) and polyester double-knit (P) fabrics, carpets (C) and filter paper (F), which are identified in Table 4.1. Practically all of these burning rate tests were run using the large cabinet version specified under the FMVSS 302 notice of proposed rule making (10) for the following reasons:

1. The horizontal burning rate tests were initiated under the previous contract, No. FH-11-7303, using the larger cabinet version; the smaller cabinet version had not been anticipated at that time. Therefore, in order to salvage these earlier data, the larger cabinet was continued in use.

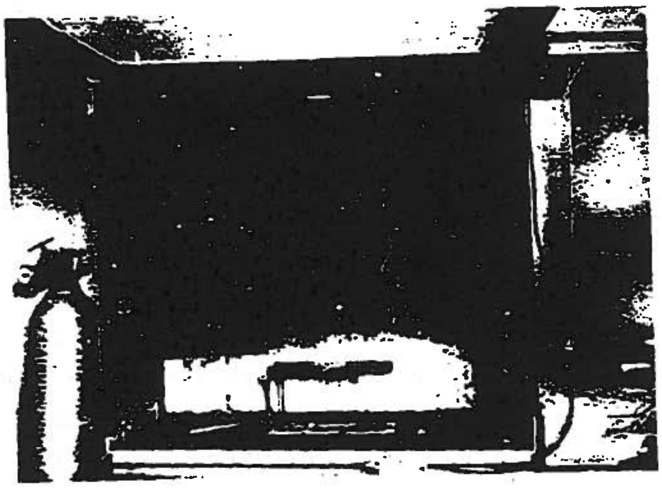


Figure 4.19. Proposed FMVSS 302 horizontal burning rate apparatus (large cabinet with front window raised).

Figure 4.20. Inclined burning rate test rack.

2. Even though the smaller cabinet tends to give slightly higher burning rates, the difference is not statistically significant as explained before.
3. The larger cabinet is more adaptable for running burning rates at inclined angles.

The principal departure from the procedure as specified in the proposed (large cabinet) standards was that all of the tests were performed under the existing laboratory conditions since facilities for maintaining the laboratory at the specified 70°F and 65 percent relative humidity were not available. The test samples themselves were either oven-dried or were preconditioned in a constant humidity-constant temperature (65 percent and 70°F) chamber. In either case, the burning rate tests were started within two minutes after removing the sample from the oven or conditioning chamber; the burning rate test was carried out at the prevailing laboratory temperature and humidity. As will be discussed later, this departure from the specified procedures is not material.

4.2.2 Scope of Burning Rate Tests

Burning rate tests in the smaller cabinet were run on (refer to Table 4.1) oven-dried samples of F-1 (one layer); CT-1 (parallel to warp); F-2 (two layer); CT-2 (parallel to warp). All other burning rate tests were performed in the larger cabinet. As indicated in Table 4.1 most of the materials were preconditioned in a chamber maintained at 65 percent relative humidity and were then run at prevailing laboratory conditions. Due to a failure in the humidity chamber, a few of the samples were preconditioned by drying in an oven; the burning tests were then run at the prevailing laboratory conditions.

All of the burning rate data are tabulated in Appendix D. Table 1 in Appendix D lists the materials, orientations of the fibers in the test samples, angle of inclination of the test if other than horizontal, and the calculated burning rates.

Table 2 in Appendix D summarizes the burning rates of the automobile fabrics which were installed in the test vehicle (1952 Dodge) used for conducting simulations of actual vehicle fires; these simulations will be discussed in Section 4.3. Table 3 in Appendix D summarizes the pertinent data for the inclined or angled burning rates by listing the material, the angle of inclination, the number of determinations, the burning rates (maximum, minimum and average), and the standard deviation of the burning rates from the average.

4.2.3 Results of Horizontal Burning Rate Tests

The maximum burning rate for each vinyl, nylon, saran, and carpet sample is given in Figure 4.21. The polyester double-knits melted but did not sustain ignition. About one-half of the nylons, one quarter of the vinyls and all of the carpet samples had maximum observed burning rates which were less than the 4 inches/minute prescribed in the federal standard for FMVSS 302.

The maximum burning rates shown in Figure 4.21 and the average burning rates shown in Figures 4.22 through 4.25 are (except for vinyl V-14) for the flame front propagating lengthwise in the direction of the decorative pattern or of the backing fabric with the normally exposed side of the fabric up. As can be seen by an examination of Table 1 in Appendix D, the burning rates for the nylons, vinyls and sarans are strongly dependent on the sample orientation: lengthwise normal, lengthwise inverted, crosswise normal and crosswise inverted. The carpets and cottons showed negligible differences with orientations; obviously the orientation does not apply to filter paper. From the standpoint of vehicle interior fires, it was decided that the lengthwise normal orientation would be the most applicable because of the way interior materials are installed for aesthetic reasons. However, the observed differences in burning rate with orientation do

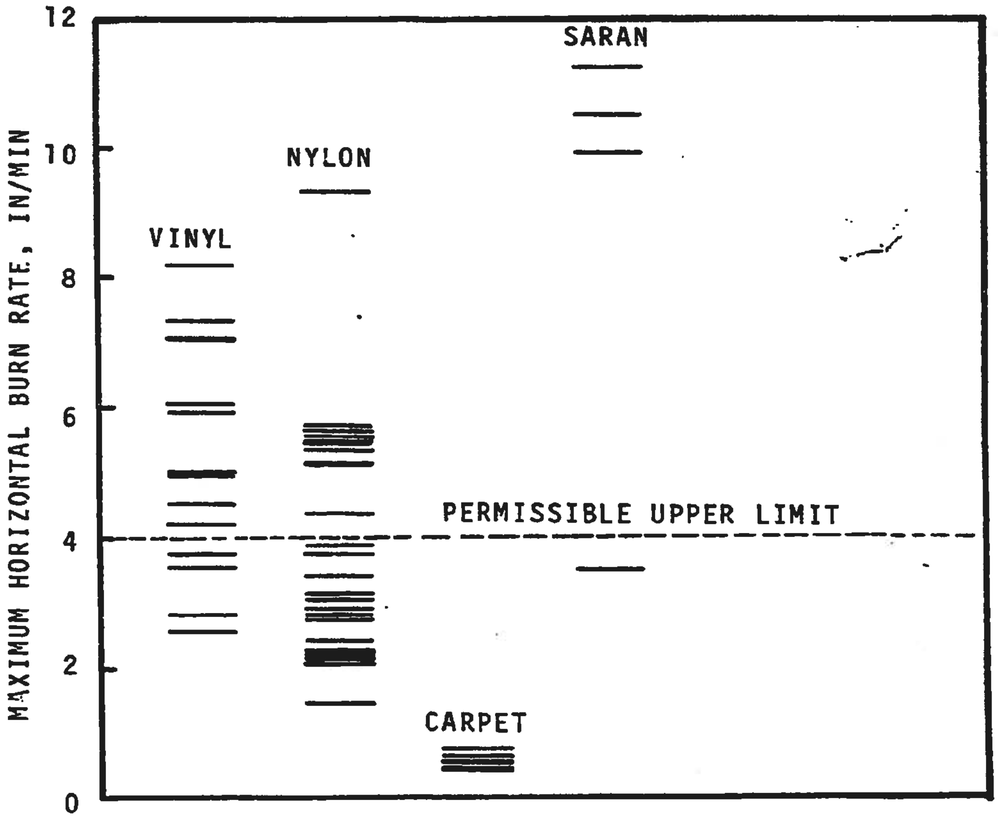


Figure 4.21. Ranges of maximum horizontal burn rates according to general material type.

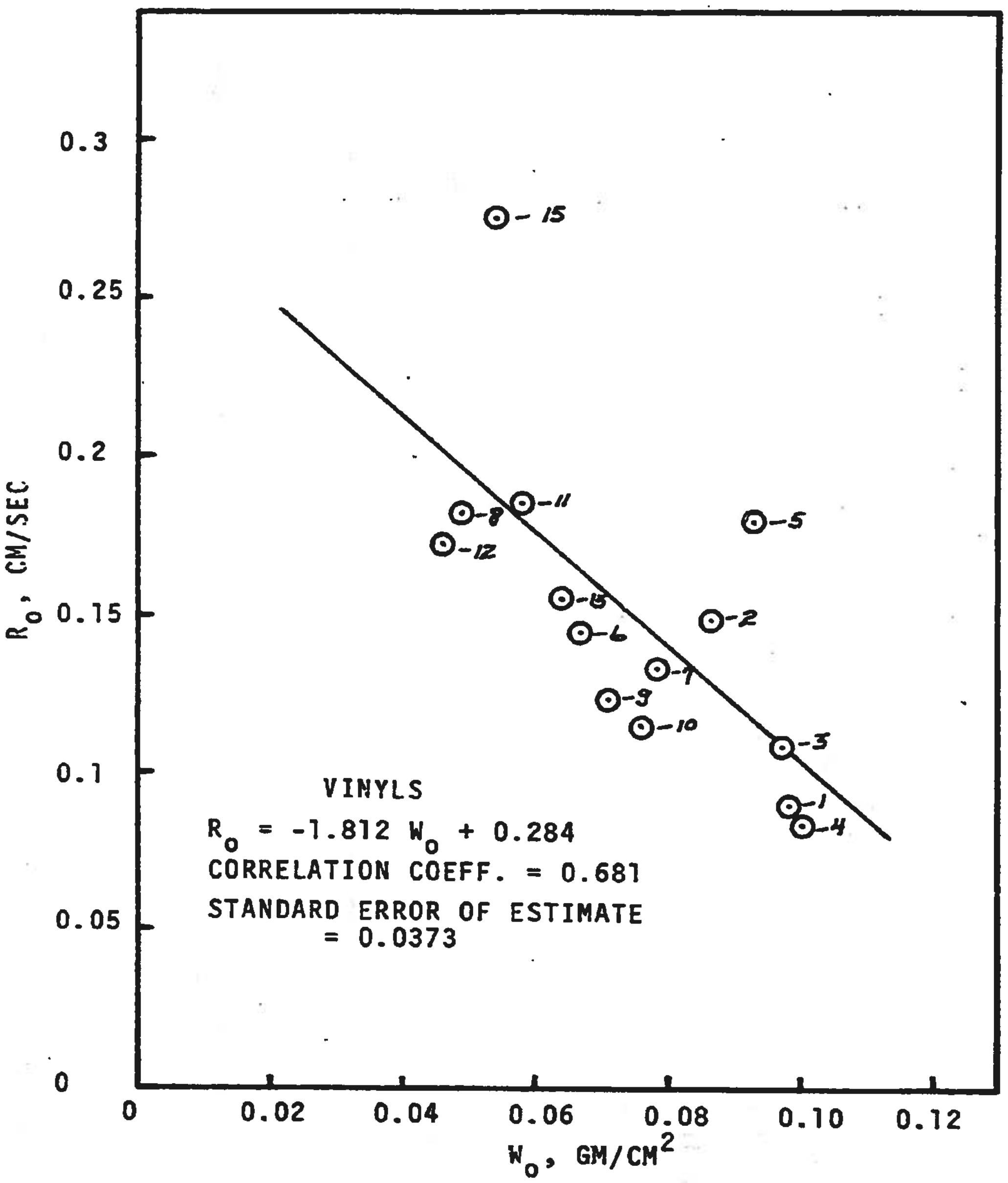


Figure 4.22. Trend in horizontal burning rate with weight for vinyls (numbers on data points identify sample).

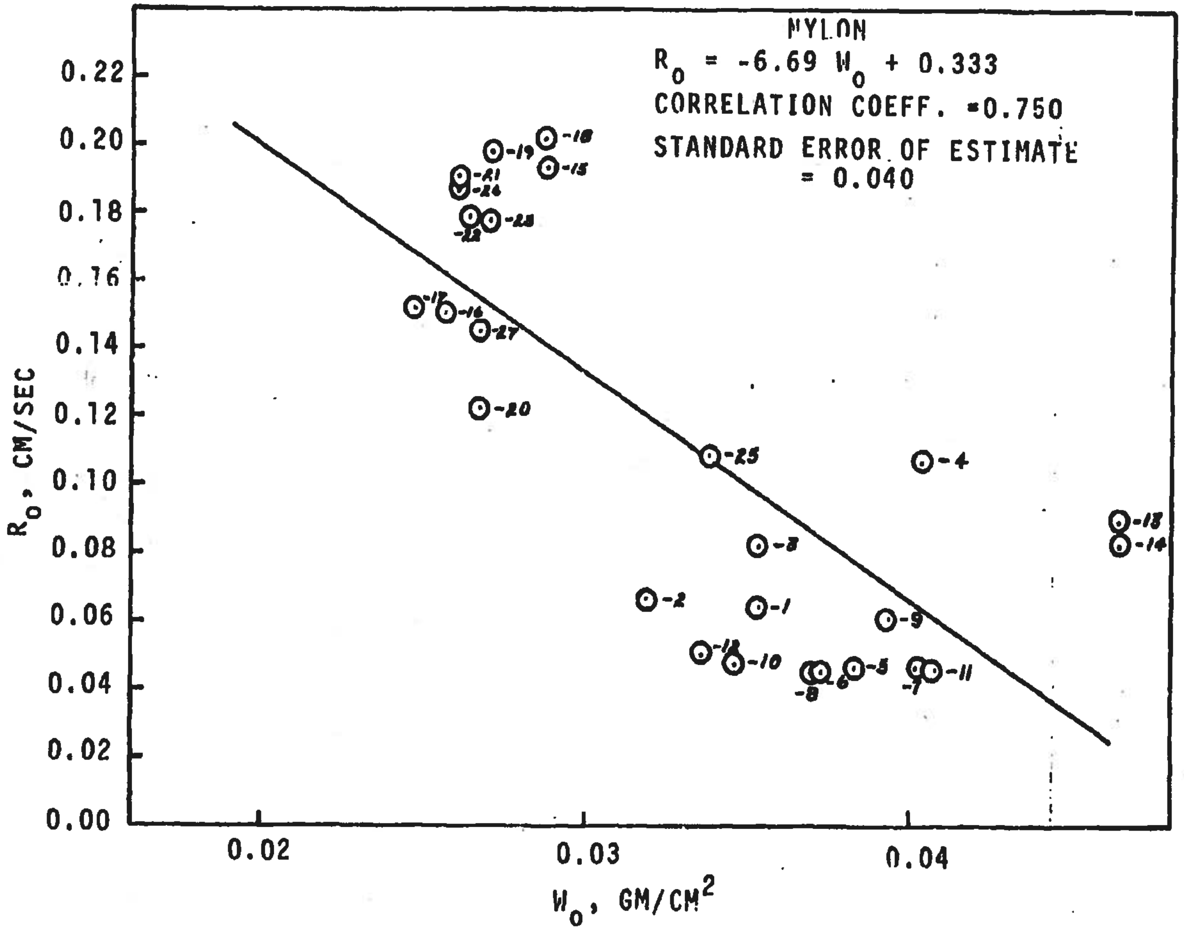


Figure 4.23. Trend in horizontal burning rate with weight for nylons (numbers on data points identify sample).

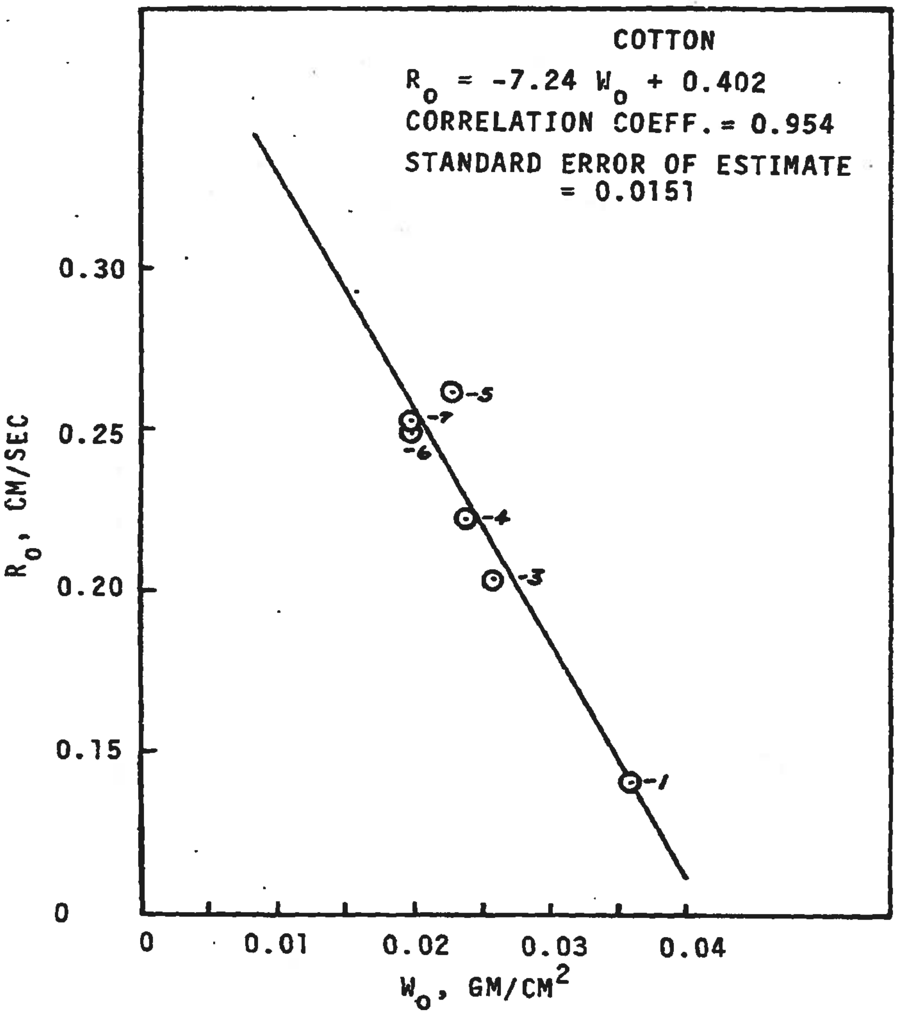


Figure 4.24. Trend in horizontal burning rate with weight for cottons (numbers on data points identify sample).

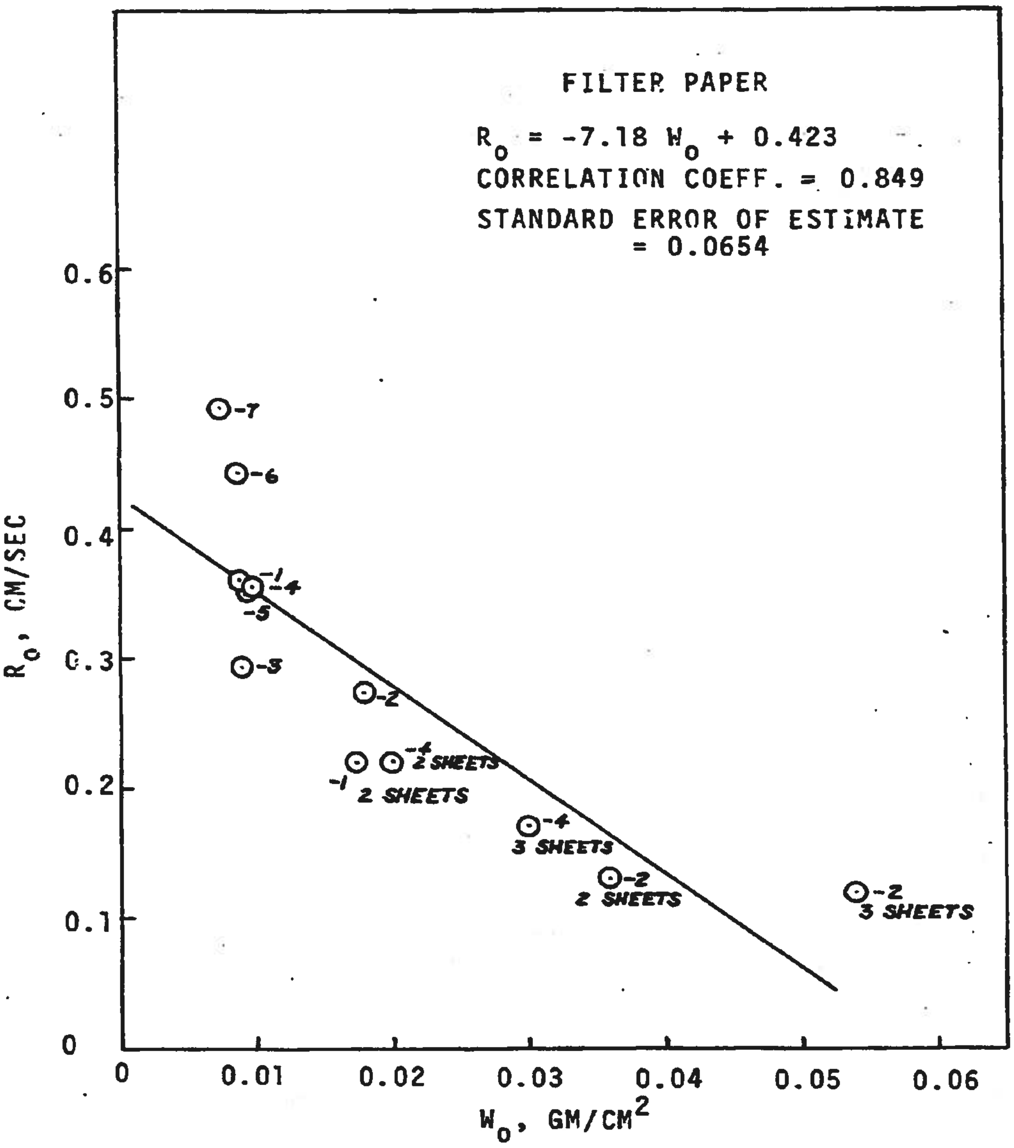


Figure 4.25. Trend in horizontal burning rate with weight for filter papers (numbers on data points identify sample).

suggest the possibilities for capitalizing on decorative pattern and surface finish to reduce flammability in a given material.

Attempts to correlate the <u>average</u> burning rates with the physical properties of the sample, such as weight per unit area, thickness, density or a combination of these properties were basically unsatisfactory (except for cotton). Nevertheless, some trends were indicated. As can be seen in Figures 4.22 through 4.25, the average burning rate appears to decrease with increasing weight although there are exceptions. The straight lines shown in these figures were derived from regression analyses of the data. The equation for the line, the correlation coefficient and the standard error of estimate are shown on the graphs. As a word of caution, none of the data should be discarded as being in error. For example, in Figure 4.22 one should not conclude that V-15 and V-5 are bad experimental data because depending on which parameter the average burning rate (R_o) is correlated against, V-15 and V-5 could "line-up" with many of the other vinyls in which case some of the other vinyls would "look bad." In fact, a plot of the average burning rate against the thickness gave a slightly better correlation coefficient, but as explained in Section 4.1, the weight measurement is by far the most reliable. The nylons afford another example of the danger in drawing a sweeping generalization. If only the heavier nylons (above 0.03 gm/cm^2) as represented by N-1 through N-14 were considered in the correlation, then the best linear fit as obtained from a multiple regression analysis would show a positive slope, indicating an opposite trend, namely that the burning rate increases with increasing weight.

The lack of an adequate correlation as indicated by the low correlation coefficients (below 0.9 except for cotton) in Figures 4.22 through 4.25 is not too surprising considering the wide variations in the chemical formulations, fabric construction and surface finish, even within one type of material.

For example, some vinyls are smooth and some have indentation patterns or perforations. Some of the vinyls have a cloth (presumably cotton) backing; others do not. Some of the nylon fabrics are weaves containing threads of various sizes; some nylons are compounded with other materials such as rayons. Essentially, the most that could be considered--but not without exceptions--is the (pre-1971) vinyls having a weight greater than 19 oz/yd^2 and (pre-1971) nylons having a weight greater than 8 oz/yd^2 will generally have burning rates below the prescribed maximum of 4 inches/minute. The higher burning rate of the vinyls as compared to the nylons is probably due to the high plasticizer content in vinyls.

On the other hand, the cotton fabrics were presumably all cotton with the principal variation being in the size and number of threads constituting the weave pattern. Cotton showed a definite decrease in burning rate with increase in weight; it is also noted that the density for all cottons was almost constant. The filter papers, although primarily cellulose, are treated with various agents to achieve certain desired properties (ashless, wet strengthened, hardened, etc.) which could account for some of the scatter in the data in Figure 4.25.

4.2.4 Reproducibility of the Horizontal Burning Rate Tests

In order to ascertain the reproducibility of the horizontal burning rate tests, a number of samples of the various materials were selected at random, and 30 horizontal burning rate determinations were made on each sample. The results are summarized in Table 4.4. As can be seen there is a wide variability in the reproducibility of the burning rates for the different materials. The standard deviation of the burning rate varies from 3.6 percent of the average burning rate for one of the filter paper samples to 50 percent of the average burning rate for one of the nylon samples.

TABLE 4.4

COMPARISON OF HORIZONTAL BURNING RATES OF MATERIALS

Material	Burning Rate, in/min Maximum	Burning Rate, in/min Minimum	Burning Rate, in/min Average	Standard Deviation in/min	Standard Deviation % of Mean
One sheet #1 Whatman Filter Paper (F-1)	9.26	7.94	8.53	0.40	4.6
Two sheets #1 Whatman Filter Paper (F-1)	6.32	4.32	5.20	0.51	9.0
Two sheets #3 Whatman Filter Paper (F-2)	3.29	2.92	3.10	0.112	3.6
Vinyl fabric (V-15)	6.67	5.36	6.05	0.46	7.6
Vinyl Fabric (V-13)	4.33	2.40	3.67	1.29	35.
Cotton fabric (CT-1)	3.52	2.54	3.02	0.28	9.4
Nylon fabric (N-25)	2.76	2.33	2.55	0.11	4.3
Nylon fabric (N-26)	5.52	3.31	4.42	0.65	15.
Nylon fabric (N-27)	9.33	1.36	3.43	1.70	50.

The magnitude of the percent variance is not necessarily dependent on either the average burning rate or the chemical classification of the material. For example, N-25 shows a 4.3 percent deviation from the mean whereas N-27 shows a 50 percent deviation. Similarly, the percent deviation for V-15 is 7.6 while for V-13 it is 35. The three filter paper samples showed burning rates with a variability from 3.6 to 9.0 percent of the mean. The largest variation was for two sheets of the Whatman No. 1 paper (F-1). It was observed during these particular tests that the two sheets tended to separate from each other during the burning test, presumably because this filter paper is very light weight. With the two sheets of the heavier Whatman No. 3 paper (F-2), this tendency was not observed, which might account for it having the lowest variability in repetitive burning tests for all the materials. Both F-1 and F-2 are designated as qualitative paper for use in standard chemical analyses; therefore, one would expect them to be the most uniform from sample to sample of all the materials tested. Yet the single sheet of F-1, which is not subject to the uncertainty of maintaining two sheets in close contact throughout the burning test, showed a higher percentage deviation from the mean (4.6 versus 3.6) than the two sheets of F-2. However, as will be explained in Subsection 4.2.6.3, this variability is probably inherent in the test procedure itself rather than the sample. Another pertinent observation from the burning tests is that materials which had a more constant burning rate over the full 10 inches, as determined by taking intermediate readings, gave the lowest variability in repetitive tests. The indication from Table 4.4 is that the horizontal burning test apparatus yields a basic reproducibility of less than 10 percent, and possibly less than 5 percent. Larger deviations are most likely caused by non-uniformities in the sample per se (which might be aggravated by surface finish or decorative patterns) rather than by the test apparatus, test procedure, magnitude of the burning rate and chemical classification of the sample since some vinyls, nylons and cottons had variabilities below 10 percent.

On the other hand, based on the variability which was observed for some of the samples, particularly the nylons and vinyls, it is apparent that a given material must be designed to have a burning rate substantially below the prescribed 4 inches/minute in order to assure that all FMVSS burning tests on this sample will not exceed this limit. Using the statistical technique known as the "One-Sided Tolerance Limits for a Normal Distribution".(12) and Table A-7 of this reference, horizontal burning rate data of nylon N-26 and vinyl V-13 were analyzed. For N-26, which has a standard deviation of 15 percent of the mean, the mean burning rate must be below 1.07 inches/minute to assure with 99 percent confidence that 99.9 percent of the samples chosen at random will burn at less than 4 inches/minute. For V-13, which shows a standard deviation of 35 percent of the mean, the mean burning rate would virtually have to be zero in order to give 99 percent assurance that 99.9 percent of the samples would burn at less than 4 inches/minute.

Obviously, the FMVSS standard of 4 inches/minute is much less onerous for uniform materials. For example, if the standard deviation is only 5 percent of the mean, a mean burning rate of 3.3 inches/minute will give 99 percent assurance that 99.9 percent of the samples will pass the 4 inches/minute requirement. For 99 percent confidence that 75 percent of the samples--with a standard deviation of 5 percent of the mean--will burn at a rate less than 4 inches/minute the mean horizontal burn rate would have to be 3.6 inches/minute. If the standard deviation is 10 percent of the mean, then for 99 percent confidence that 75 percent of the samples will not exceed the 4 inches/minute burning rate, the mean burning rate will have to be less than 3.3 inches/minute. In this case the two sheets of Whatman filter paper No. 3 (F-2), cotton CT-1, and nylon N-25 would be the only materials listed in Table 4.4 that could pass the standard of 4 inches/minute.

These results are in general agreement with the statistical analyses reported by others (13). Basically, the FMVSS 302 standard of 4 inches/minute is more exacting with respect to the non-uniformity or variability of burning rates within a given material. Thus, the real merit of the FMVSS 302 standard lies in its commendable requirement for uniformity in the material rather than its imposition of a pass-fail criterion of 4 inches/minute which admittedly is somewhat arbitrary.

4.2.5 Inclined Burning Rates

Thus far, attention has been given only to horizontal burning rates as specified by FMVSS 302. In contrast the American Society for Testing and Materials specifies several tests for different surface positions or angles of inclination (14). Since in a vehicle interior fire the combustible materials can burn and propagate a flame in many directions ranging from horizontal to vertical, a number of burning rate tests were performed at various angles of inclination from the horizontal (-30°, -15°, 0°, 15°, 30°, 45°, 60° and 75°). In order to obtain a good representation of the burning rates and to determine whether there was any change in the variability of the test results with angle of inclination, 30 burning tests were run for most of the samples. The samples chosen for these tests were vinyls (V-13 and V-14), nylons (N-24, N-25 and N-26) and filter paper (F-1). Complete burning rate data are given in Table 1 of Appendix D. Note that for vinyl V-13 and nylons N-24, N-25 and N-26, the tests were run lengthwise (in the direction of the decorative pattern or of the backing fabric) with the normally exposed side of the fabric up. For V-14, the burning rate was measured lengthwise but with the normally exposed side down or inverted. A summary of these results, giving the angle of inclination, the number of burning tests run, the average (arithmetic mean), maximum and minimum burning rates observed, the standard deviation, and the percent deviation from the mean, is presented in Table 3 of Appendix D. As can be seen in this table, the burning rate and absolute variability of the test results increases with increasing angle of inclination. Thus, the lowest burning rate and standard deviation occurs at -30°, for which the flame propagates downward at an inclination of 30° from the horizontal; the highest burning rate and, in most cases, the standard deviation, occur at 75° upward. Attempts to run burning rates at 90° were not successful because the flame engulfed almost the entire sample shortly after ignition and made identification of the position of the flame front at any time virtually impossible.

The inclined burning rates are summarized in graphical form in Figures 4.26 through 4.31. A convenient and simple parameter for representing the inclinations is the sine of the angle since it varies from 0 to 1 and is negative for the downward inclinations. The spread between the maximum and minimum observed burning rates are shown by the vertical lines and the arithmetic average burning rate by the solid dot. A visual fit of the data through the average burning rates for all positive angles is more than adequately represented by a straight line. The equations for these lines are shown on the graphs. For those materials which had a measurable horizontal burning rate, R_o, the burning rate, R, at any positive angle can be roughly approximated by

$$R = (9 \sin \theta + 1) R_o \qquad (4.7)$$

where θ is the angle of inclination above the horizontal.

Thus, as an order of magnitude estimate, the vertical burn rates are at least 10 times the horizontal rate. This result is to be expected since when the sample is inclined upward from the horizontal the combustion gas flow is concurrent

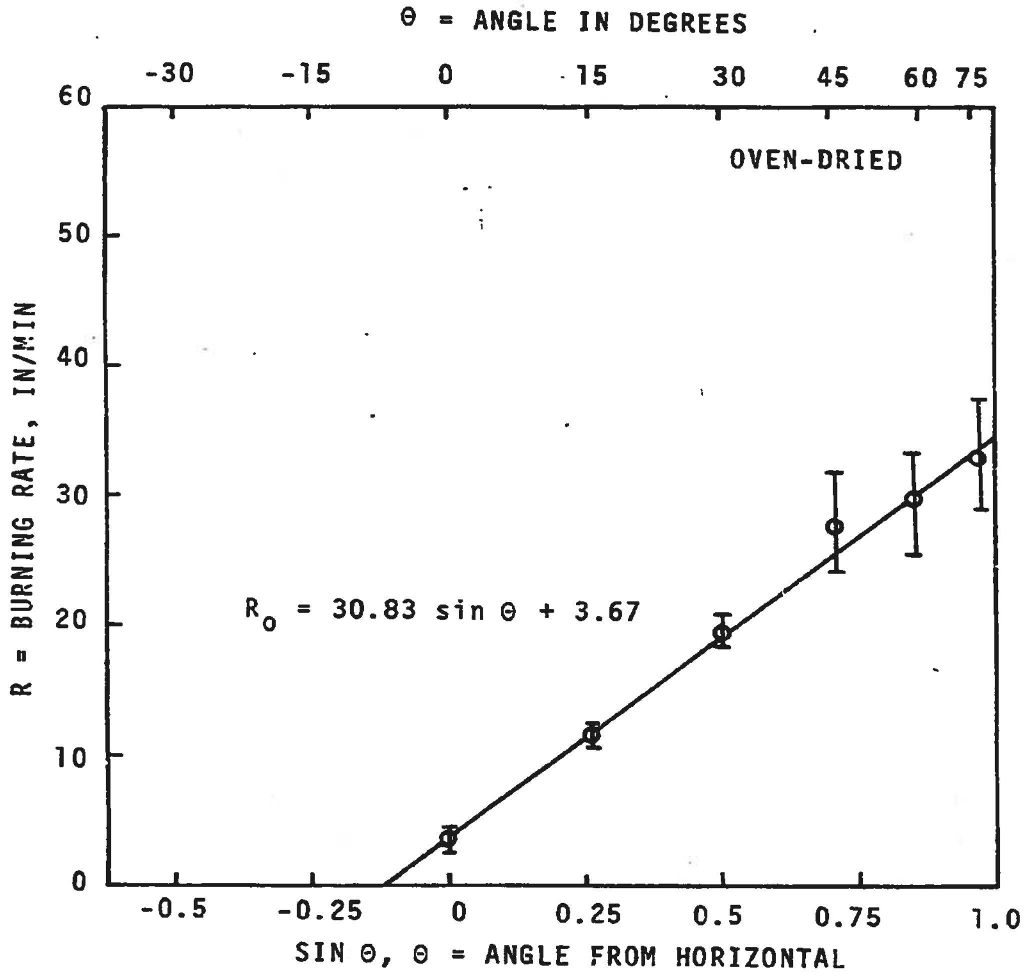


Figure 4.26. Vinyl V-13 burning rates (lengthwise-normal). 30 determinations on each angle.

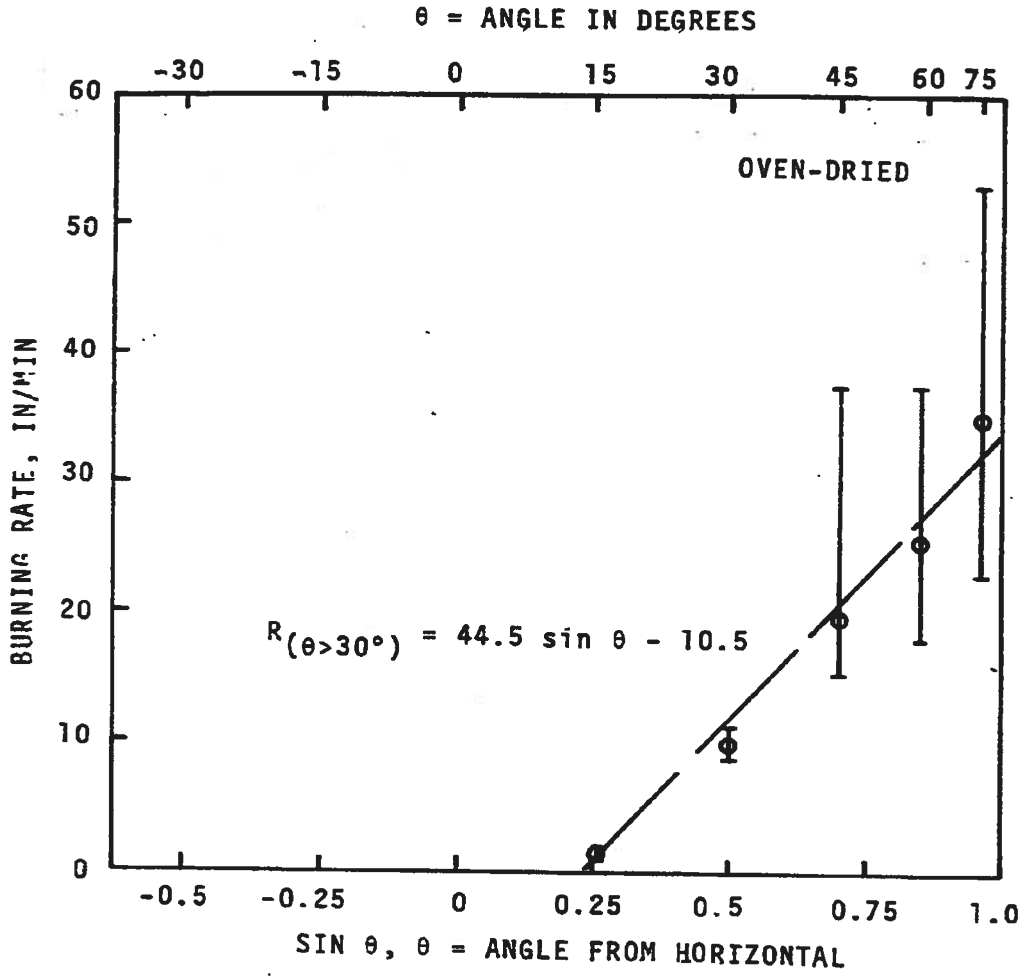


Figure 4.27. Vinyl V-14 burning rates (lengthwise-inverted). 30 determinations each angle.

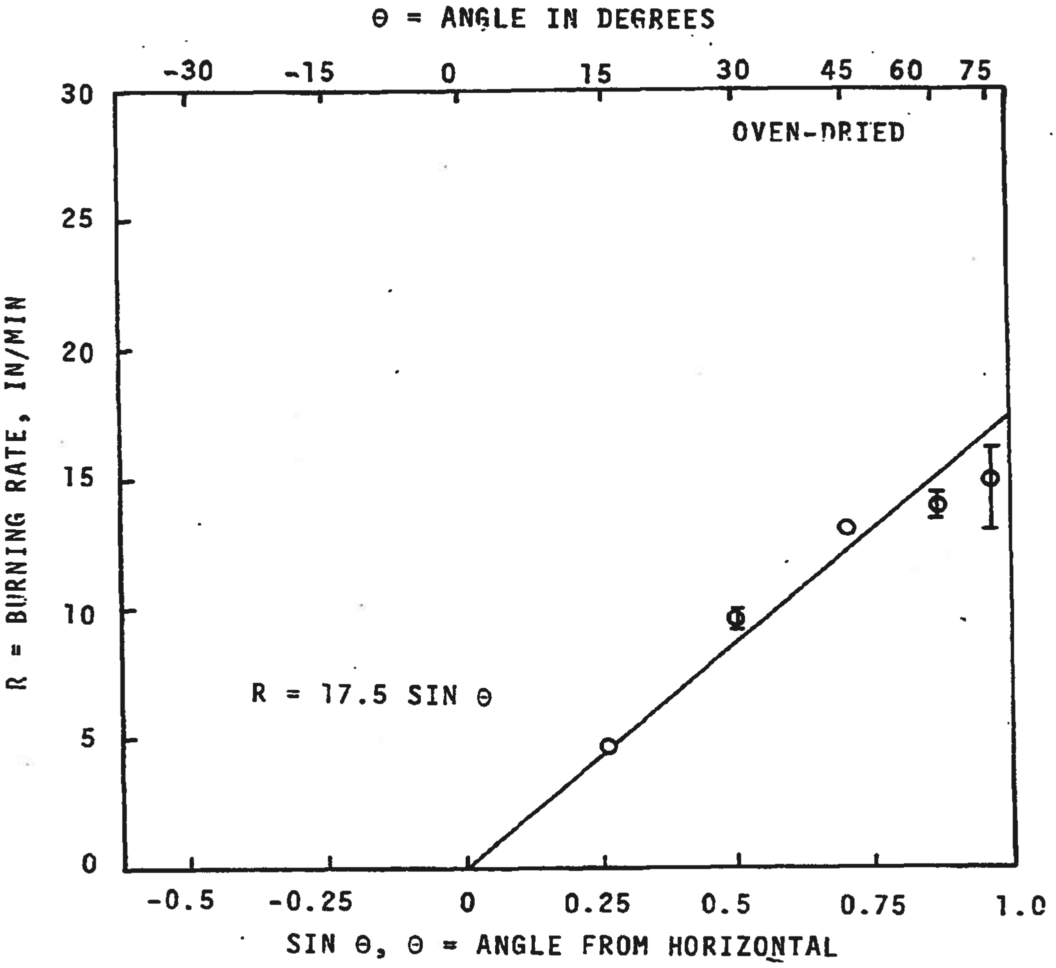


Figure 4.28. Nylon N-24 burning rates (lengthwise, normal). 3 determinations on each angle.

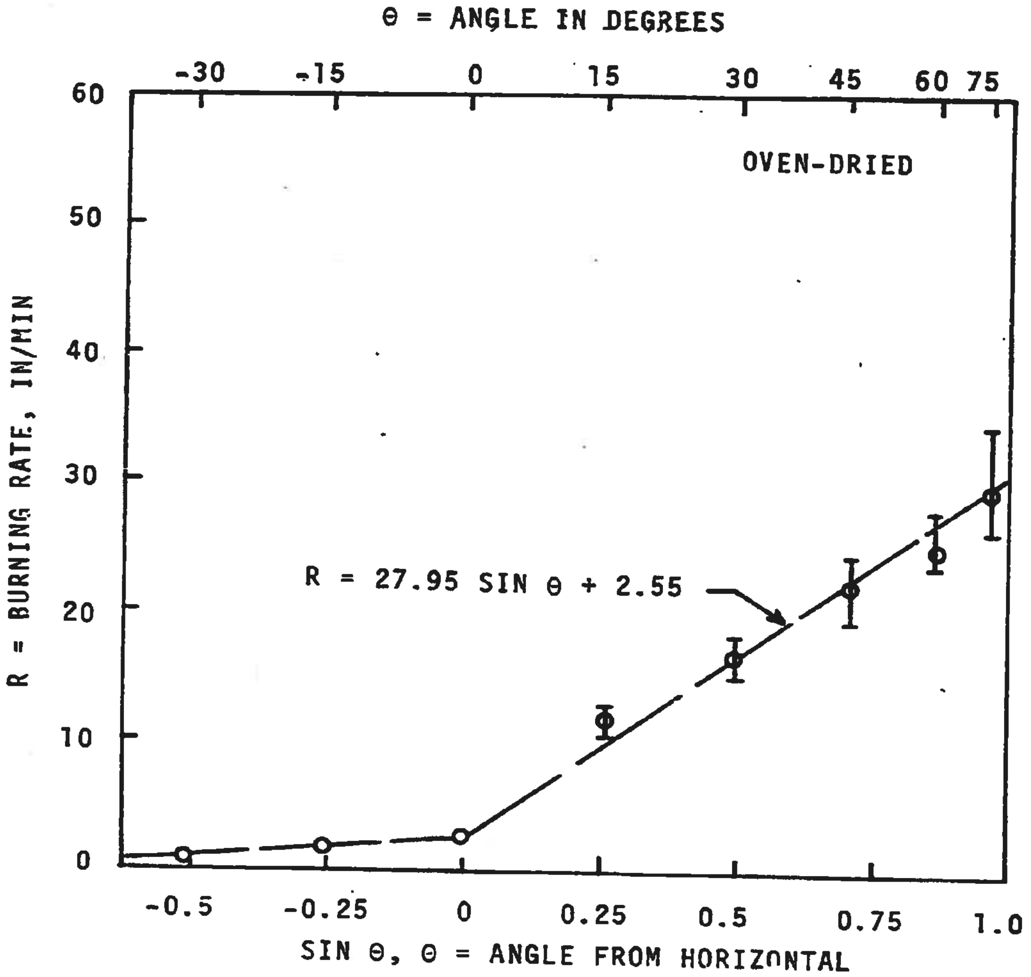


Figure 4.29. Nylon N-25 burning rates (lengthwise-normal). 30 determinations on each angle.

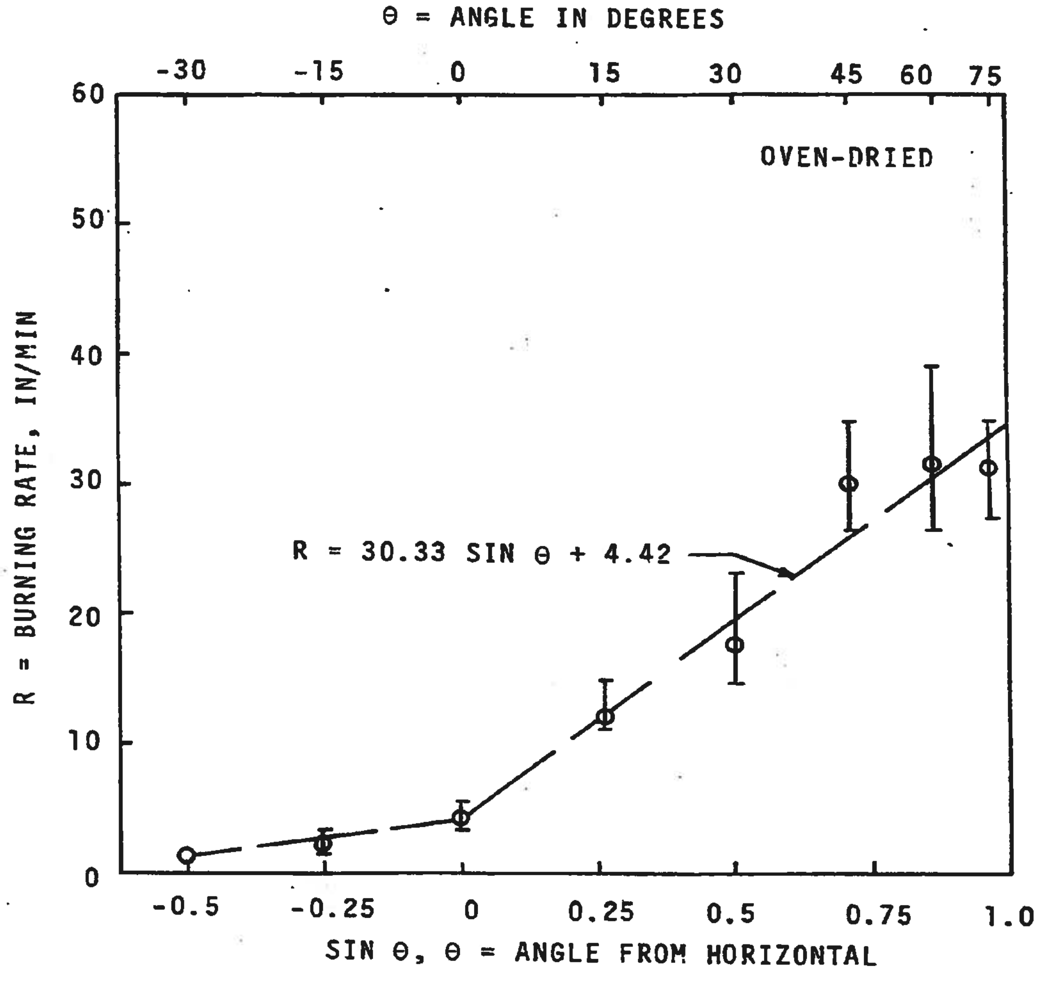


Figure 4.30. Nylon N-26 burning rates (lengthwise-normal). 30 determinations on each angle.

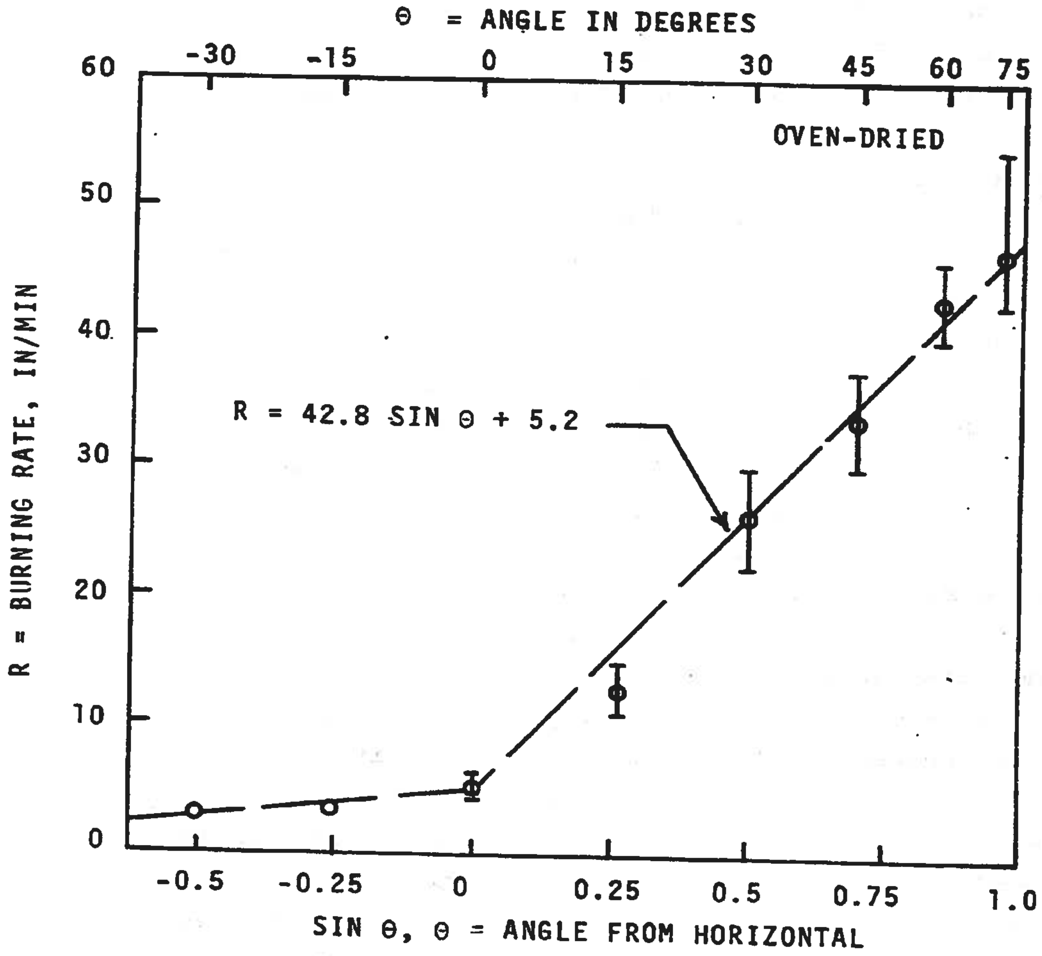


Figure 4.31. Filter paper F-1 (two sheets) burning rates. 30 determinations each angle.

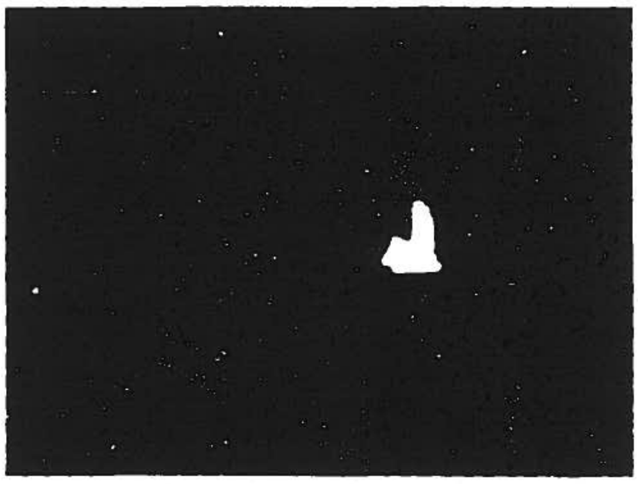
with the direction of the flame front propagation. In this case the hot combustion gases preheat the sample ahead of the flame front. When the sample is inclined downward from the horizontal, the hot combustion gases move in the opposite direction from the flame front travel and the incoming combustion air which feeds the flame front cools the sample ahead of the flame front.

The difference between the horizontal and inclined (about 45°) burning is visually demonstrated by the photographs in Figure 4.32. The burning specimen is balsa wood, 2 inches wide and 1/16 inch thick. The horizontal burning rate was about 6 inches per minute; the burning rate at 45° was too fast to observe with any degree of accuracy.

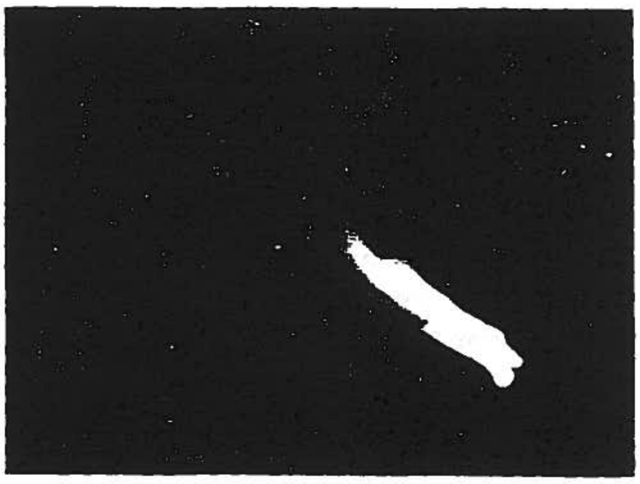
From these inclined burning rate tests it is evident that a material which meets the 4 inches/minute horizontal burning limit of FMVSS 302 could conceivably burn at 40 inches per minute in the vertical direction. Furthermore, as can be noted from Figure 4.27 (V-14) and Figure 4.28 (N-24), materials which do not burn in the horizontal position can have high burning rates in the inclined position. It is interesting to observe that even at 15° the burning rate of V-14 was under 1 inch/minute, whereas in the vertical position it had increased to 34 inches/minute. N-24 showed a negligible burning rate in the horizontal position, about 4 inches/minute at 15° and 15 inches/minute at 75° inclination. Since both vinyls and nylons are installed in vehicle interiors such that they could be susceptible to burning in the vertical mode, the relevance of the FMVSS 302 limit of 4 inches/minute for horizontal burning becomes remote.

4.2.6 Effect of Other Variables

As explained before, much of the variability in measuring burning rates on a particular sample was attributed to non-uniformities in the material itself. Since it is known



a. Horizontal



b. Inclined 45° upward

Figure 4.32. Comparison of the visual characteristics of the flame for horizontal and inclined burning (balsa wood).

that other variables can also alter the rates, this section will consider the effects of moisture content, orientation of the fibers in the sample, heat losses from the burning specimen, width of the sample, wind and baffles. The primary purpose of these special studies was to obtain a better understanding of the test parameters.

4.2.6.1 Moisture content: The FMVSS 301 standard prescribes conditioning the burning test sample for 24 hours at 70°F and 50 percent relative humidity. Samples of nylons (N-13, N-14 and N-19), vinyl (V-6) and saran (S-3) were preconditioned at various levels of humidity between 0 and 100 percent, following which horizontal burning rate tests were run. Computer cards and poster board, which are known to absorb moisture, were included in these tests for comparison purposes.

The results are summarized in Figure 4.33, from which it is evident that the burning rate decreases with increasing moisture as would be expected. For all practical purposes the nylons and the sarans are insensitive to moisture. The vinyl (V-6) shows a decrease in burning rate from 4.3 inches/minute at zero humidity to 2.8 inches/minute at 100 percent relative humidity; this difference is attributed to the cotton backing. Likewise, the affinity of foam backings to moisture could affect the burning rate of the fabric. (Burning rate tests run on foams at ambient conditions showed a spread of 3 inches/minute for latex to 15 inches/minute for polyurethane.) The computer cards and poster boards show marked decreases in burning rate with increasing humidity. Since in a real life situation the relative humidity in a vehicle interior can range from 0 to 100 percent, it is not clear why the FMVSS 302 standard prescribes a 50 percent humidity. Specifying oven-dried samples would not only simplify the test procedure considerably, but it would also constitute a more meaningful test from the standpoint of safety.

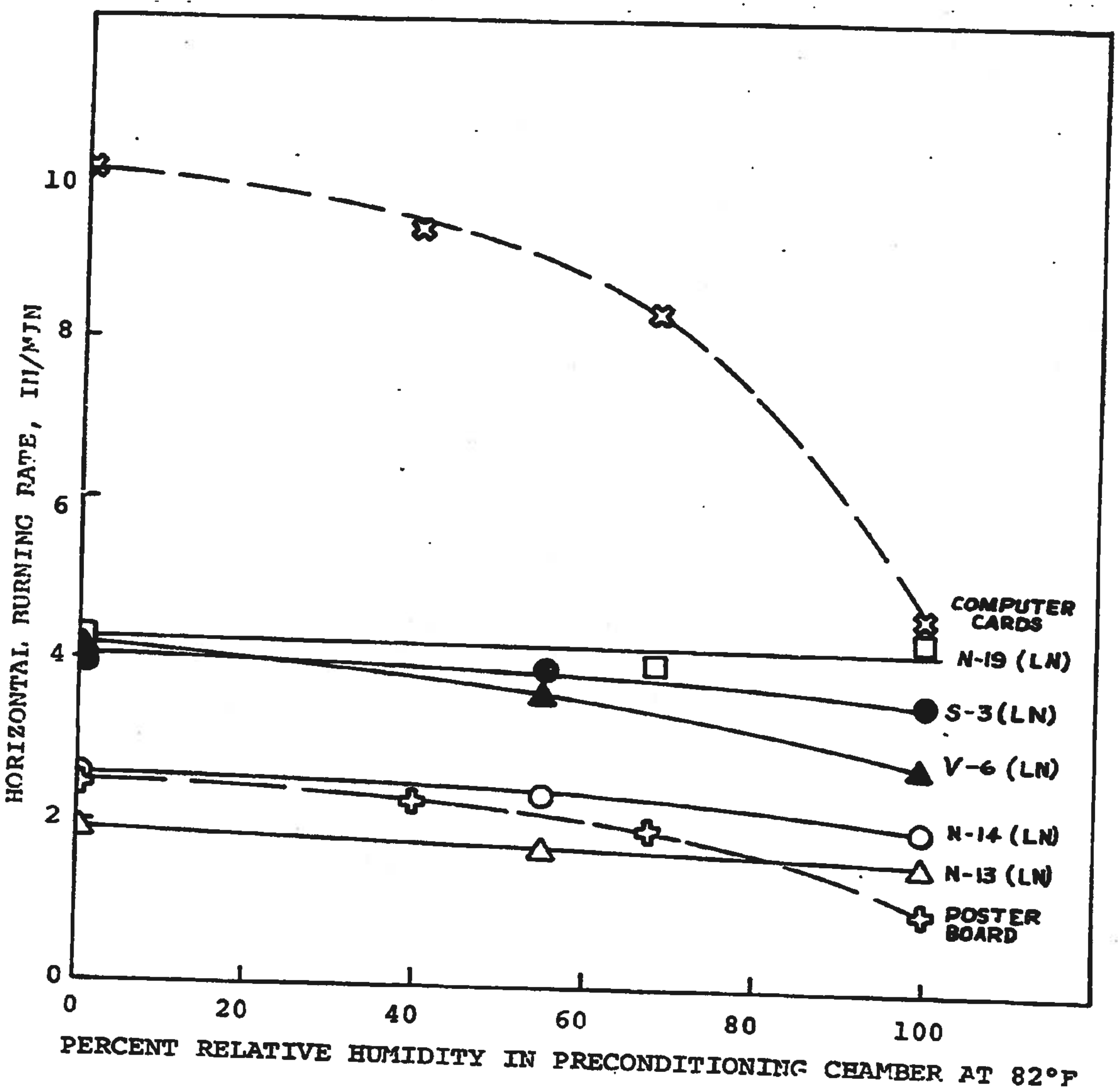


Figure 4.33. Effect of moisture content on horizontal burning rates.

4.2.6.2 Orientation of the fibers: As mentioned previously, the horizontal burning rates for the nylons, vinyls and sarans are, in many instances, strongly dependent on the sample orientation. Although the burning rate correlations in this section are based on the lengthwise normal orientation (flame front propagating in the direction of the decorative pattern or of the backing fabric with the normally exposed side of the fabric up) an examination of Table 1 in Appendix D reveals that the maximum burning rates for nylons, vinyls and sarans are more likely to be observed in a direction other than lengthwise normal as indicated below:

Lengthwise Normal (LN):	6 nylons and 2 vinyls
Lengthwise Inverted (LI):	5 nylons and 7 vinyls
Crosswise Normal (CN):	2 nylons, 1 vinyl and 3 sarans
Crosswise Inverted (CI):	10 nylons, 2 vinyls and 1 saran

In some cases the difference between the maximum and minimum horizontal burning rates was about a factor of 2.

To illustrate these differences, the horizontal burning rates for nylon N-26 are summarized below. In addition to the four principal orientations, samples were also cut on a 45° bias so that both the Bias Normal (BN) and Bias Inverted (BI) could be run, primarily to determine the manner of propagation of the flame front.

Burning Rates, inches/minute

	LN	LI	CN	CI	BN	BI
	4.15	5.96	2.16	2.85	4.55	4.70
	5.39	7.37	2.09	3.03	4.46	4.75
	4.67	6.13	2.26	2.71	3.77	5.53
AVERAGE:	4.74	6.49	2.17	2.86	4.26	4.99

As can be seen, the burning rate for the bias orientation in either the normal or inverted position lies between the arithmetic average of the burning rates in the lengthwise and crosswise directions and the maximum burning rate for that surface position (for N-26, the lengthwise direction for both normal and inverted positions).

For all horizontal burning tests run in either the lengthwise or crosswise orientations the flame front advanced uniformly across the full width of the sample with some lagging evident at the edges adjacent to the hold-down clamp, indicating heat losses to the metal. However, when the sample was burned in the bias orientation, the flame front advanced faster along one edge than the other. These two modes of burning are sketched in Figure 4.34. In an actual vehicle interior fire the flame front will advance primarily in the direction of the bulk air currents and secondarily along the direction of fastest burning.

4.2.6.3 Insulated hold-down clamp: As is evident in Figure 4.34, the flame front tends to lag at the edges adjacent to the hold-down clamp which indicates a possible heat loss at the edges. For a sample freely suspended in air in the horizontal position, the flame front advances more rapidly along the edges than in the interior. In order to ascertain the effect of insulating the metal hold-down bars from the sample, double thicknesses of asbestos paper conforming to the U-shaped clamp (Figure 4.15a) were inserted between the sample and the holder on both the top and bottom side. The test sample in this case was 2 sheets of Whatman #1 filter paper, F-1. Thirty repeat burning tests were run. The results are compared with the earlier runs in which no insulation was used (see Tables 1 and 3 in Appendix D).

Condition	Number of Tests	Burning Rate, in/min Average	Burning Rate, in/min Maximum	Burning Rate, in/min Minimum	Standard Deviation	Percent Deviation
Uninsulated	30	5.20	6.32	4.32	0.51	9.0
Insulated	30	5.20	6.02	4.95	0.24	4.5

Although the average burning rate (arithmetic average of 30 determinations) was identical for both cases, the standard deviation and percent deviation from the mean were about

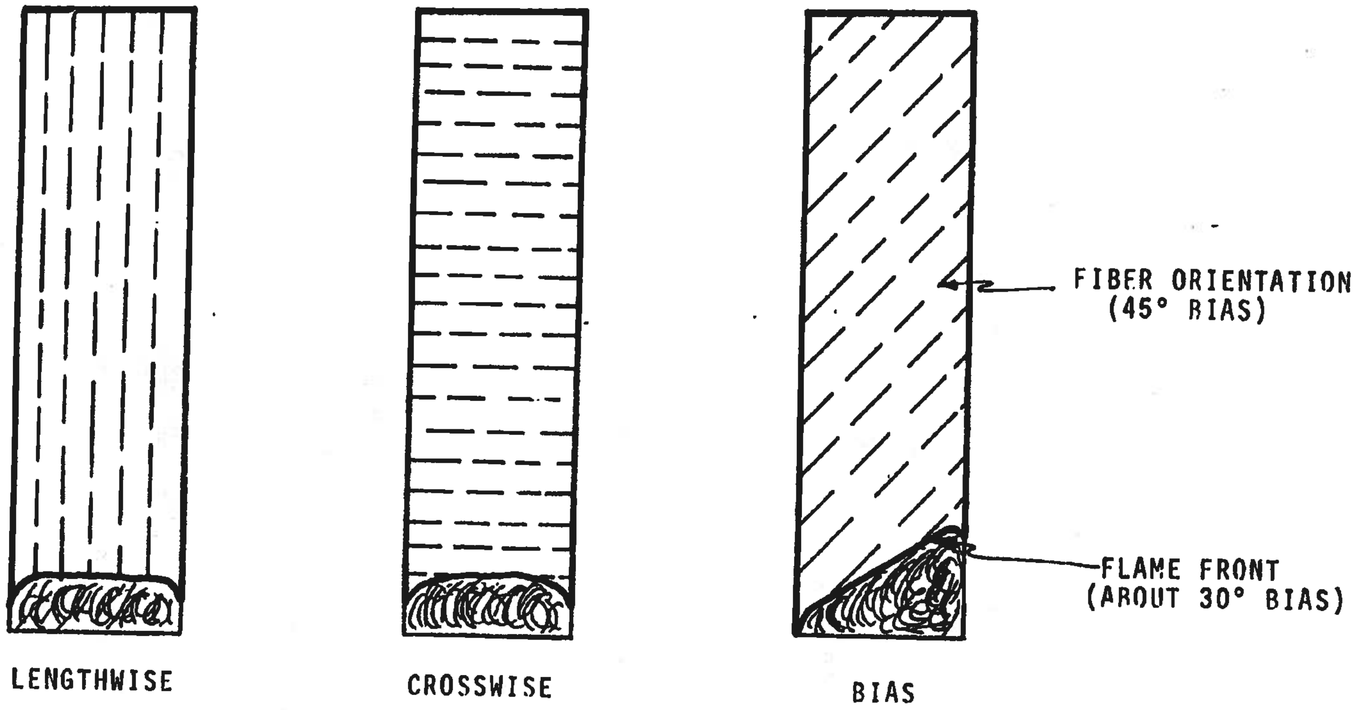


Figure 4.34. Comparison of flame front advance for different fiber orientations.

one-half as much for the insulated edges as compared to the uninsulated (FMVSS 302) procedure. To the extent that this test typifies all sample materials, insulating the sample edges might reduce the variability in the test.

4.2.6.4 Width of sample: In the specifications for FMVSS 302, the sample measures 4 inches wide by 14 inches long. Since the hold-down bar on either side is one inch wide, the burning width of the sample is 2 inches. Since the test apparatus cannot be adjusted for sample width, a makeshift sample holder was devised. A U-shaped retainer was formed from standard concrete blocks (3-1/2 x 7-1/2 x 15-1/2 inches) as shown in Figure 4.35. Asbestos insulation was used to separate the sample from the concrete blocks underneath and the lead weights on top. With this arrangement, any width of sample could be accommodated simply by moving the concrete blocks. The concrete block apparatus was first "calibrated" against the standard (except for insulation) apparatus and then burning tests were run at several widths on medium weight cotton. The results are summarized below.

	Standard Test Except for Insulation	Concrete Block Apparatus			
Burning Width of Sample, inches	2	2	4	6	8
Average Burning Rate inches/minute	6.15	3.97	4.41	4.51	4.53

As can be seen, the concrete block apparatus gives a much lower burning rate for the two-inch sample than the standard test does. The reason for this difference is largely due to the fact that the burning sample in the concrete block set-up was shielded both by the side and transverse blocks; consequently, circulation of air underneath the sample was inhibited. Apparently, the side blocks exert the dominating effect since with the transverse block removed the burning rate was the same

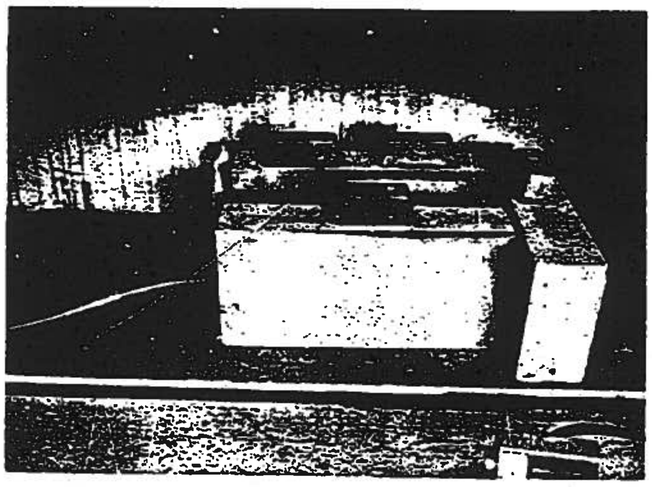


Figure 4.35. Concrete block burning rate apparatus.

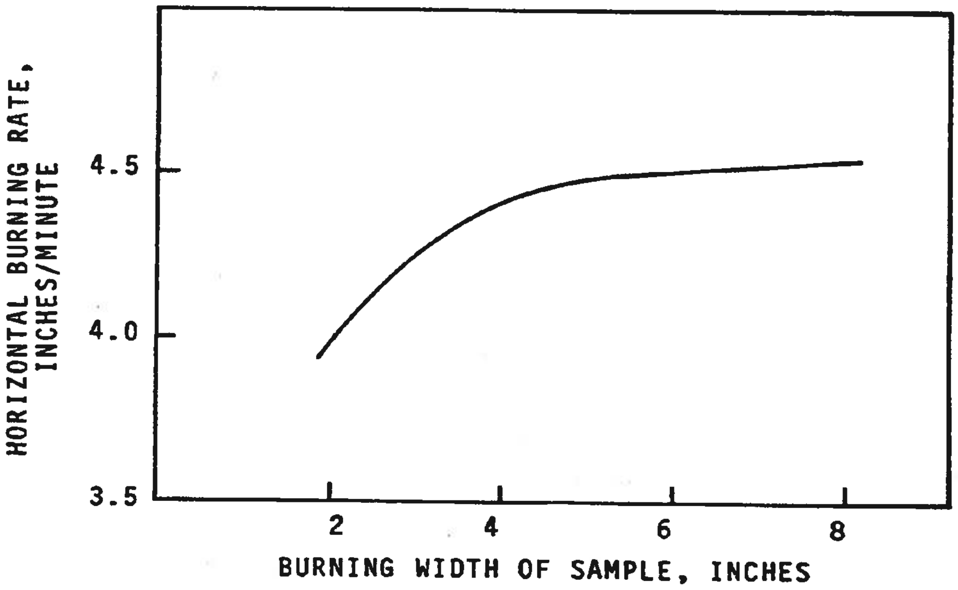


Figure 4.36. Effect of sample width on burning rate.

as for the transverse block in place. In the standard burning rate apparatus, the air is free to circulate underneath the sample from all sides. In most respects, the concrete block set-up may be more nearly representative of the burning conditions in a vehicle interior since one side of the fabric will generally have limited access to air.

The effect of sample width on burning rate is shown in Figure 4.36. Note that the burning rate increases rapidly between 2 inches and 4 inches; thereafter the burning rate appears to level off with width. This increase in burning rate with width can be expected since the geometric view factor for radiative transfer between two intersecting planes (plane of the fire and plane of the sample) increases as the width of the planes increases.

4.2.6.5 Wind: It is well known that vehicle interior fires propagate much more rapidly if a window or door is open. (The flow-through ventilation system in late model vehicles could have a similar effect.) In fact, Rothermel found in his studies on fire spread in wildland fuels (2) that a wind velocity of 12 miles/hour could increase the horizontal burning rate by a factor of 100 or more.

A brief study of the effect of wind on the standard FMVSS 302 burning rate test was made. Briefly this test consisted of blowing air along the top and bottom surface of the sample with a variable speed fan. Prior to igniting a sample, the air velocity near the midpoint of the sample was measured with an anemometer for three settings of the rheostat on the fan. The maximum wind velocity attainable was 190 feet/minute or slightly over 2 miles/hour. Tests were run with the air flowing in the same (positive) direction and then in the opposite (negative) direction. Four burning rate determinations were made at each condition. The results are tabulated below and are summarized in Figure 4.37.

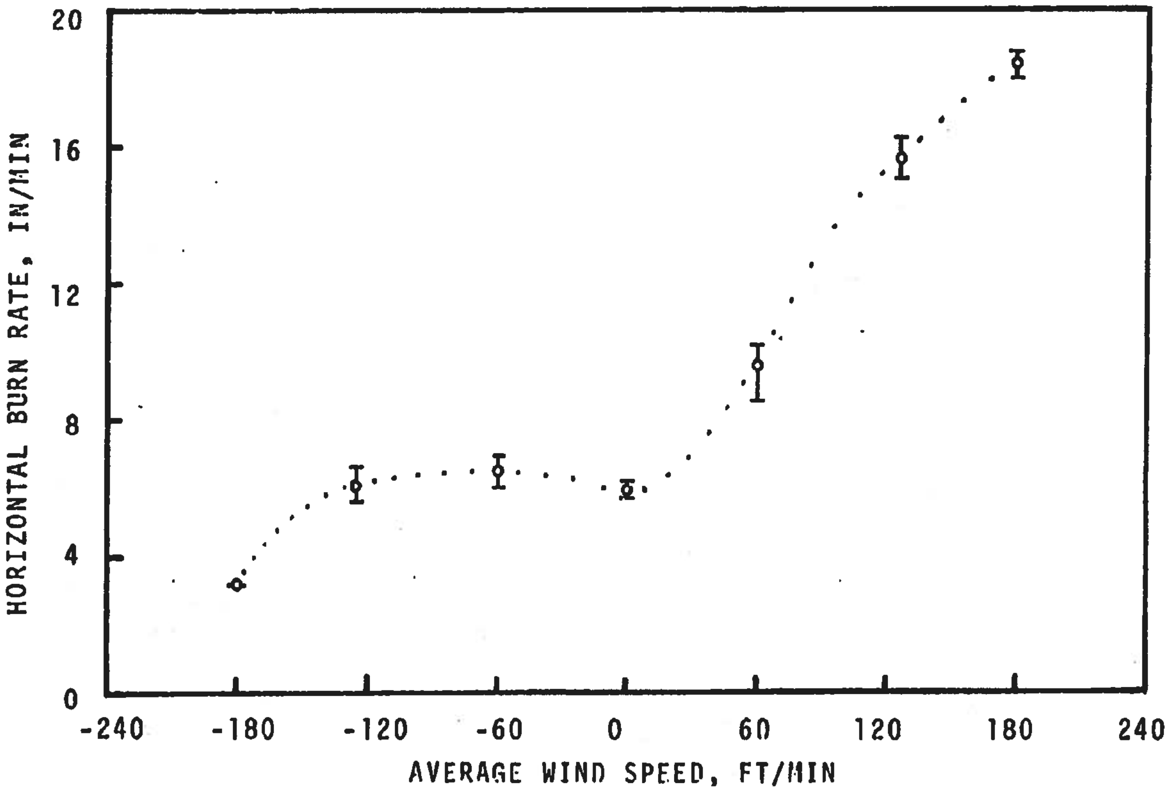


Figure 4.37. The effect of wind on the burning rate of medium weight cotton (lengthwise-normal).

Wind Velocity feet/minute	Average Burning Rate, inches/minute	Standard Deviation	Percent Deviation from the Mean
0	5.94	0.186	3.1
+ 50 to + 70	9.57	0.815	8.5
+120 to +130	15.61	0.478	3.1
+170 to +190	18.41[a]	0.301	1.6
- 50 to - 70	6.53	0.315	4.8
-120 to -130	6.12[b]	0.375	6.1
-170 to -190	3.13[c]		

[a] At this velocity the flame on the top side of the sample "blew-off" and only the flame underneath the sample remained.

[b] Only 3 determinations made.

[c] Only one determination since all other attempts led to extinguishment. For the one successful run, there was no visible flame on the top side, only underneath.

Although these wind velocities were about 2 miles/hour, they do represent an upper limit for this size of sample since at the highest velocities in either the positive or negative direction, a flame was visible only underneath the sample but not above the sample. In burning tests under no-wind conditions a flame is visible both above and below the sample as shown in Figure 4.32.

4.2.6.6 Baffles: From the tests run with the concrete block apparatus and the tests on wind effects, the accessibility of the sample to free air movement greatly influences the burning rate. To explore these observations further, a series of tests were run using baffles. Briefly the baffle consisted of a thin strip of cardboard covered with aluminum foil; the width of the strip was 2 inches, the same as the sample.

The tests with the baffles consisted of holding one edge in direct contact with the sample and manually moving it so that it remained approximately 1/8 inch ahead of the advancing flame front. Three different sets of tests were run with the baffles:

1. Baffle on top side only.
2. Baffle on bottom side only.
3. Baffles on both top and bottom simultaneously.

A double thickness of filter paper was used as the burning sample for all tests. The results are sumarized below:

Test Condition	Average Burning Rate, in/min
No baffles	5.6
Top baffle	3.2
Bottom baffle	2.0
Top and bottom baffle	1.9

It is evident from these results that the baffle reduced the burning rate considerably, with the bottom baffle being more effective in this respect than the top baffle. In fact, when the bottom baffle was allowed to approach the advancing flame front within less than about 1/8 inch, the burning sample was extinguished; on the other hand, it was possible to move the top baffle into the flame front without extinguishment. Thus, the burning sample relies mostly on the flame underneath to supply the requisite propagating heat flux for maintaining the burning process.

Another visual observation of interest is that the flame underneath remained attached to the sample and was blue in color over its full length, indicating an adequate supply of air. The flame on the top appeared to burn above the sample surface. Only the thin leading edge of this flame was blue while the remainder was the typical yellow-orange hue. Evidently, the supply of air to all parts of the top flame was hindered by the rising column of combustion gases. Similar differences have been observed in the free convective cooling of a flat plate which is hot on one face and cold on the other. A factor of two difference has been observed in the convective heat transfer coefficient for laminar flow depending on whether the hot surface is facing up or down.

4.2.7 Correlation of Burning Rates with Ignition Data

As stated in Section 4.1, the burning process or flame propagation is generally believed to proceed by a series of successive ignitions; however, the direct quantitative relationship between burning rate and ignition measurements has not been elucidated heretofore. The purpose of this section is to demonstrate how these two sets of measurements are related and applied by means of a mathematical model.

4.2.7.1 Derivation of the model: In the OURI ignition test, the sample is irradiated at a constant monitored flux and the elapsed time to ignition is recorded as the ignition time. These measurements are repeated for several different incident flux levels in order to establish the relationahip between ignition time and radiant flux. As explained previously, the incident radiant flux is converted into an absorbed flux by applying the corrections for absorptivities and transmissivities (Equation 4.6). In a more refined analysis, the absorbed flux should be corrected further to account for heat losses and changes in absorptivities during the course of the ignition tests in order to obtain the flux which is actually retained in the specimen. The techniques for making this additional refinement have been developed by Wesson (5), but they were not employed here in the interest of simplicity.

Thus, the ignition measurements provide a functional relationship between the ignition time, t, and the absorbed flux, H_a. An energy balance on the ignition sample is:

$$(H_a t)\ A_y = C_p\ (T_{ig} - T_o)\rho(\delta\ A_y) \qquad (4.9)$$

where H_a = absorbed energy flux, cal/cm^2-sec
t = ignition time, sec
A_y = area of the sample face exposed to the flux, cm^2
C_p = specific heat of the original sample, cal/gm-

T_{ig} = average temperature of the sample at ignition, °C

T_o = initial temperature of the sample at the start and is taken to be ambient temperature, °C

ρ = initial density of the sample, gm/cm^3

δ = thickness of the sample, cm

The justification for Equation 4.9 is quite involved and is based on extensive studies at the OURI Flame Dynamics Laboratory by Havens (15) and Brown (16) using differential scanning calorimetry combined with thermogravimetric analyses. Normally, the right hand side of Equation 4.9 would include terms to account for the heats of vaporization and pyrolysis during the preheating period prior to reaching ignition. However, because of the high heating rates, and therefore the fast ignition times involved in the burning process, the heat effects accompanying the decomposition processes can be ignored, in which case Equation 4.9 constitutes a definition for the temperature of ignition. Furthermore, for the present application, the initial specific heat and initial density of the sample are valid for use in Equation 4.9 (15, 16). By rearranging Equation 4.9, the defining equation for ignition temperature is obtained:

$$T_{ig} = \frac{H_a t}{\delta \rho C_p} + T_o \qquad (4.10)$$

Since δ, ρ, C_p and T_o are assumed to be constants, it is clear that T_{ig} is dependent on the product $(H_a t)$. As can be seen in Figure 4.38, $(H_a t)$ is a strong function of t; vinyl V-7 was chosen arbitrarily to illustrate this point. The ignition temperature of vinyl V-7 calculated by Equation 4.10 is generally within the range determined by laboratory tests.

Contrary to common usage, it is misleading to treat the ignition temperature as a unique, characteristic property of the material. According to Equation 4.10, T_{ig} represents

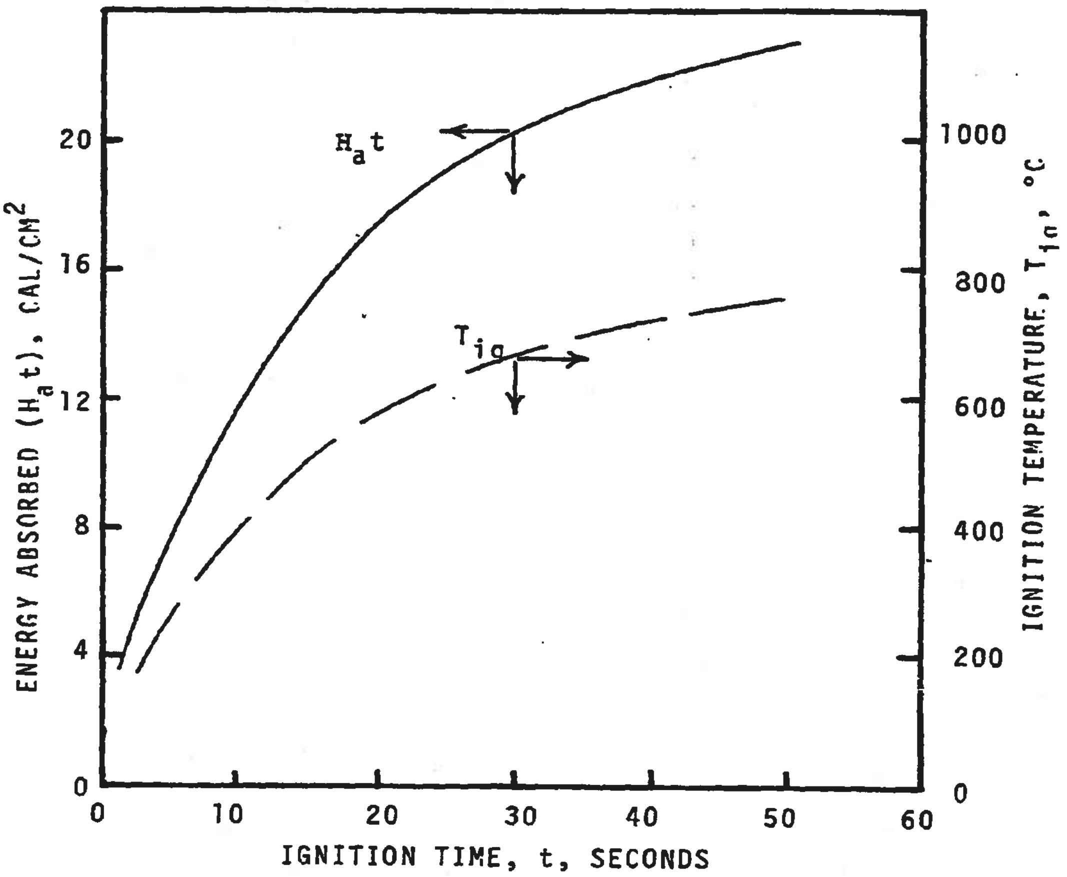
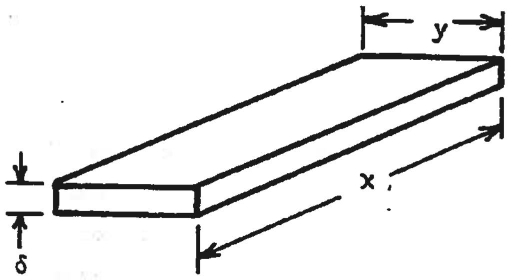


Figure 4.38. The variation of energy absorbed per unit area with time to ignition for Vinyl V-7.

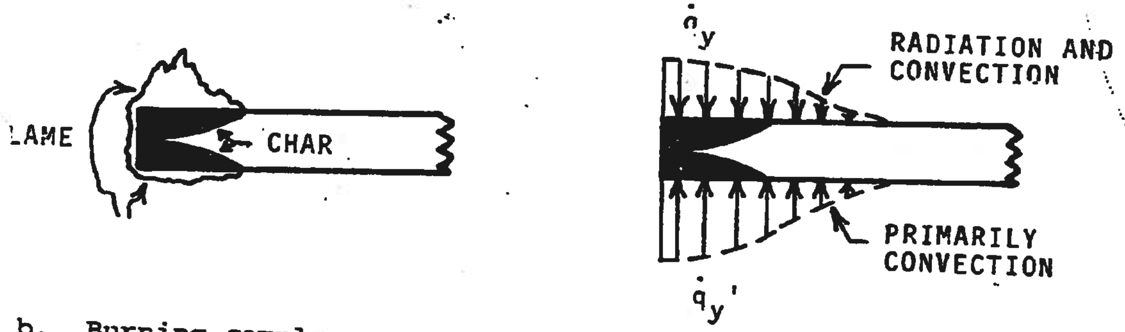
the integrated average temperature of the specimen at ignition. At the instant of ignition, the temperature at the surface exposed to the radiation flux is very high, on the order of several hundred degrees for short ignition times which correspond to high heat fluxes. At the same time, the temperature of the rear face of the sample will be close to ambient. In other words, short ignition times (high fluxes) result in a very steep temperature gradient near the exposed face which then levels off over the remaining thickness of the sample: consequently, the average or ignition temperature is low. On the other hand, long ignition times (low heat fluxes) produce more uniform heating throughout the thickness of the sample so that the average or ignition temperature will be higher and more nearly equal to the median temperature between the front and rear faces. Ignition temperatures calculated from Equation 4.10 at low incident heat fluxes (long ignition times) are more likely to be in error because the heat losses (by convection and reradiation), which are not accounted for, are more significant. Considerable variation in ignition temperatures is found within one classification of materials. For example, the ignition temperature which is characteristic of the burning process (to be discussed subsequently) for vinyl V-15 is 77°C, whereas for vinyl V-6 the corresponding characteristic ignition temperature is 117°C.

As was demonstrated by Wesson (5), a simplified mathematical model for transient, one dimensional heat conduction through an infinite, solid slab of an inert, opaque material constitutes an acceptable representation of the ignition process. Since the burning process is visualized as a series of successive ignitions, it is reasonable to assume that a similar mathematical approach is applicable to flame propagation.

In the FMVSS 302 horizontal burning test, it was observed that the sample, Figure 4.39a, ahead of the flame front is preheated both from above and below by the advancing flame

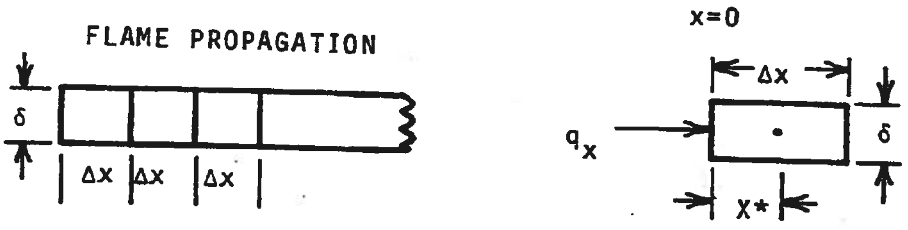


a. Test sample



b. Burning sample

c. Vertical heat fluxes



d. Discrete ignition elements

e. Individual element at incipient ignition when $x = 0$, $T = T_f$ and $x = X^*$, $T = T_{ig}$.

Figure 4.39. Schematic of flame propagation.

front, Figure 4.39b. Based on the study on the effect of baffles (Subsection 4.2.6.6), the vertical fluxes, $\dot{q}_y$ and $\dot{q}_y'$ (Figure 4.39c), are not necessarily equal nor are they uniform over the full length of the preheated section. Consequently the resultant of the vertical fluxes is a horizontal propagating flux $\dot{q}_x$ (Figure 4.39e).

To facilitate development of a physical model which is simple, and therefore tractable mathematically, the sample is broken up into discrete ignition elements of length Δx (Figure 4.39d). The flame is then visualized to propagate by a periodic series of successive "jumps" of distance (Δx). Other approaches for modeling the burning process are presented by Frandsen (17). An individual element of thickness, δ, and length, (Δx), is isolated in 4.39e. The element is initially at a uniform temperature which is equal to the ambient temperature, T_o. The left face of this element is then exposed to a temperature, T_f, which is assumed to be the equivalent black body temperature of the flame. The resulting horizontal flux, $\dot{q}_x$, induces a temperature gradient in the element; heat losses from the element are assumed to be negligible. When the integrated average temperature of the element reaches the ignition temperature, T_{ig}, the element ignites. The position in the element where the temperature is T_{ig} is designated as $x = X^*$. The elapsed time (from the start) to establish the ignition temperature, T_{ig}, at $x = X^*$, is designated as $t = t^*$. Once this element is ignited, the entire ignition process is initiated and repeated in the next, adjacent element. The rate at which these "jumps" occur determines the quasi-steady state burning rate which is then defined as

$$R_o = X^*/t^* \qquad (4.11)$$

For the sake of simplicity, at the sacrifice of mathematical elegance and rigor, the following analysis is adopted.

Assume that the one dimensional model for transient heat conduction through a semi-infinite, inert and opaque slab applies. Assume also that the heat capacity, c_p, thermal conductivity, k, and density, ρ, are independent of temperature and position. An energy balance on the element yields

$$\kappa \frac{\partial^2 T}{\partial x^2} = \frac{\partial T}{\partial t} \qquad (4.12)$$

where κ is the thermal diffusivity $(\frac{k}{\rho c_p})$

Initial condition: $t = 0,\ T = T_o$ for all x (4.13a)

Boundary conditions: $t > 0,\ T = T_s$ at $x = 0$ (4.13b)

$t > 0,\ T = T_o$ at $x = \infty$ (4.13c)

The solution to Equation 4.12 subject to the conditions imposed by Equations 4.13 is well-known:

$$\frac{T - T_o}{T_s - T_o} = 1 - \text{erf}\ \frac{x}{2\sqrt{\kappa t}} \qquad (4.14)$$

For the problem of particular interest here, $t = t^*$, $x = X^*$, $T = T_{ig}$, $T_s = T_f$, so that

$$\frac{T_{ig} - T_o}{T_f - T_o} = 1 - \text{erf}\ \frac{X^*}{2\sqrt{\kappa t^*}} \qquad (4.15)$$

Combine Equations 4.15 and 4.11

$$\frac{T_{ig} - T_o}{T_f - T_o} = 1 - \text{erf}\ \frac{R_o\sqrt{t^*}}{2\sqrt{\kappa}} \qquad (4.16)$$

Recalling the energy balance on the sample in the <u>ignition test</u>

$$T_{ig} = \frac{H_a t}{\delta \rho C_p} + T_o \qquad (4.10)$$

It is clear from Equation 4.10, and Figure 4.38, that for each absorbed flux, H_a, there is a corresponding ignition time, t.

In the burning process, which is visualized as a succession of ignitions, there is a unique or characteristic ignition time, $t = t^*$, and a corresponding absorbed flux, $H_a = H_a^*$, which applies to the burning process. Therefore, Equation 4.10 is specialized to

$$(T_{ig} - T_o) = \frac{H_a^* \, t^*}{\delta \rho C_p} \qquad (4.17)$$

Combining Equations 4.17 and 4.16,

$$\frac{H_a^* \, t^*}{(T_f - T_o)\, \delta \rho C_p} = 1 - \operatorname{erf} \frac{R_o \sqrt{t^*}}{2\sqrt{\kappa}} \qquad (4.18)$$

Equation 4.18 gives a relationship among the burning rate, the characteristic ignition or burning time and the heat flux required to maintain propagation subject to all of the assumptions imposed in the derivation. The general ignition parameters, H_a and t, are absolute quantities in the sense that they are independent of the test apparatus and procedure. On the other hand, as will become more evident subsequently, the burning rate is a relative quantity that is defined by the particular test apparatus and procedure. This distinction deserves special emphasis since it appears to have been overlooked previously.

4.2.7.2 Consequences of the model: Preliminary calculations with Equation 4.18 indicated that the characteristic burning times were on the order of fractions of a second for most of the materials. Obtaining ignition data with the desired level of accuracy at times below 1 or 2 seconds is virtually impossible with the OUPI ignition cabinet. Furthermore, as explained in Subsection 4.1.3, the extrapolation of ignition data outside the range of 2 to 60 seconds--or the use of Equation 4.5 for this purpose--can be "risky." However, for short ignition times on the order of fractional seconds, and for the range of thicknesses of the vehicle interior materials, the error function term in Equation 4.5 approaches a constant value of one. Furthermore, since the density raised to the 0.2 power is fairly constant for most of the vehicle interior materials, then it is deduced from Equation 4.5 that at low ignition times,

$$\sqrt{t} \approx \text{constant}/H \qquad (4.19)$$

Also as $H \to \infty$, $\sqrt{t} \to 0$. Thus, a plot of $\sqrt{t}$ versus $1/H$ for low ignition times should give a straight line passing through the origin. Using the ignition data for times under about 10 seconds, graphs of $\sqrt{t}$ versus $1/H$ were made for each material. These data were fitted visually by means of a straight line passing through the origin. The slopes of the straight lines generated for each material were then measured. It was assumed that this slope was valid for the fluxes and ignition times corresponding to H_a^* and t^*; thus

$$\text{slope} = S^* = H_a\sqrt{t} = H_a^* \sqrt{t^*} \qquad (4.20)$$

This result is substituted into Equation 4.18 to give

$$\frac{S^* \sqrt{t^*}}{957\, w_o c_p} = 1 - \text{erf}\, \frac{R_o\sqrt{t^*}}{2\sqrt{\kappa}} \qquad (4.21)$$

where $w_o = \rho\delta$, $T_f = 982°C$ (1800°F), and $T_o = 25°C$ (4.4). The following thermal properties were assigned:

	C_p in cal/gm-°C	κ in cm^2/sec
Vinyls	0.4	1.06×10^{-3}
Nylons	0.4	1.06×10^{-3}
Cottons	0.34	1.06×10^{-3}
Filter paper	0.34	1.06×10^{-3}
Carpets	0.4	1.06×10^{-3}
Sarans	0.4	1.06×10^{-3}

The results of these trial and error calculations with Equation 4.21 to find the characteristic burning time, t*, and corresponding fluxes, H_a*, are summarized in Table 4.5

The most valuable consequence of these computations is that the product $R_o\sqrt{t^*}$ was found to be remarkably constant within each class of materials. This result is not surprising because it, in fact, constitutes a calibration factor for the particular burning rate apparatus and procedure, in this case the FMVSS 302 standard. (Although the burning rate tests were conducted in the proposed standard having the large cabinet, the calibration factor would only be in error by a few percent for the adopted standard (the small cabinet) based on the comparisons reported in Table 4.3.) However, if another burning rate apparatus were used, such as the concrete blocks (Subsection 4.2.6.4), several samples within each classification of materials would have to be subjected to burning rate tests in order to establish the calibration factor for each material.

Basically, the design of the burning rate apparatus and the specified test procedure define a particular kind of burning rate. Thus, every burning rate test and procedure is just as valid as any other one, and it has not been established at this point whether one test and procedure bears a simple and constant relationship to another for all materials. Of ultimate concern is that it is difficult--if not impossible--to relate directly any particular burning test to the so-called "real-life" situations.

4.2.7.3 Generalized predictions: The calibration factors derived for each class of materials can be applied to generate specialized equations for predicting the horizontal burning rates. The calibration factor, C_F, is given by

$$C_F = R_o\sqrt{t^*} \qquad (4.22a)$$

$$\text{or } \sqrt{t^*} = C_F/R_o \qquad (4.22b)$$

TABLE 4.5

CHARACTERISTIC BURNING TIMES AND CORRESPONDING FLUXES

Material	Measured			Calculated		
	W_o gm/cm^2	S*	R_o cm/sec (LN)	t* sec Eq 4.21	H_a* cal/cm^2-sec Eq 4.20	$R_o \sqrt{t^*}$
Vinyl						
V-1	0.098	2.83	0.0902	0.86	3.10	0.0837
2	087	3.75	1482	32	7.07	0839
3	096	2.33	1092	69	2.83	0907
4	100	3.37	0843	88	3.55	0791
5	093	2.83	1808	27	5.50	0940
6	067	4.37	1452	28	8.31	0775
7	078	3.75	1334	37	6.60	0808
8	050	3.47	1820	18	8.47	0783
9	072	4.15	1230	39	6.64	0768
10	076	3.47	1143	48	5.25	0792
11	085	3.75	1854	19	9.13	0812
12	047	3.33	1706	22	7.18	0792
13	064	3.90	1550	27	7.53	0803
15	054	3.30	2750	11	10.14	0896
					C_F =	0.0824 (AVG)
Nylons						
N-1	0.035	4.45	0.0644	0.63	5.54	0.0511
4	040	4.45	1060	0.36	7.42	0636
5	039	4.45	0457	1.01	4.14	0460
7	040	3.33	0457	1.35	2.87	0531
8	038	4.27	0436	1.20	3.84	0477
9	039	4.05	0601	0.81	4.44	0541
10	035	3.90	0474	1.00	3.99	0475
11	041	4.70	0453	1.07	4.54	0468
12	034	3.90	0500	0.91	4.19	0477
13	046	4.05	0876	0.54	5.46	0640
14	047	5.00	0813	0.52	6.91	0589
					C_F =	0.0527 (AVG)
Sarans						
S-3	0.0741	4.45	0.154	0.271	8.54	0.0802
4	0376	3.28	106	402	5.17	0672
					C_F =	0.0737 (AVG)

TABLE 4.5--Continued

Material	Measured w gm/cm^2	 S*	 R_o cm/sec (LN)	Calculated t* sec Eq 4.21	 H_a* cal/cm^2-sec Eq 4.20	 $R_o\sqrt{t^*}$
Carpets						
C-1	0.0685	5.71	0.0224	3.15	3.22	0.0398
2	0748	5.00	0	32.80	0.87	--
3	0725	3.33	017	7.20	1.24	0456
4	1018	5.71	019	5.33	2.47	0439
5	1022	3.70	0	112.53	0.35	--
6	0637	6.25	020	3.05	3.58	0350
7	0661	5.00	018	4.38	2.39	0376
8	1055	5.42	022	6.65	1.33	0568
9	0617	6.00	029	2.71	3.64	0478
					C_F =	0.0438 (AVG)
Cottons						
CT-1	0.036	3.37	0.141	0.24	6.87	0.0686
2	026	2.83	204	12	8.19	0724
3	024	2.90	223	10	8.78	0724
5	023	3.08	262	08	11.16	0724
6	020	2.72	249	08	9.77	0711
7	020	2.50	253	09	8.20	0745
					C_F =	0.0720 (AVG)
Filter Paper						
F-1	0.0088	1.97	0.361	0.0375	10.12	0.0699
2	0179	2.86	273	0665	11.09	0704
3	0088	2.13	294	0480	9.73	0644
4	0101	2.22	358	0395	11.17	0702
5	0094	2.47	350	0355	13.10	0658
6	0087	2.07	444	0260	13.08	0716
7	0075	2.22	487	0205	15.58	0697
					C_F =	0.0689 (AVG)

Substituting Equation 4.22b on the left side and Equation 4.22a on the right side of Equation 4.21 gives, after rearranging terms,

$$R_o = \left[\frac{C_F}{957\, C_p \left(1 - \mathrm{erf}\, \frac{C_F}{2\sqrt{\kappa}}\right)}\right] \frac{S^*}{w_o} \tag{4.23}$$

$$R_o = C^* \, [S^*/w_o] \tag{4.24}$$

The constant C* is defined by the bracketed term in Equation 4.23 and contains, in addition to the calibration factor, the specific heat and the thermal diffusivity as given previously. The values for C_F, or average $R_o\sqrt{\epsilon}$, are shown in Table 4.5 for each class of materials, namely

C_F = 0.0824 (vinyls)
= 0.0533 (nylons)
= 0.0737 (sarans)
= 0.0438 (carpets)
= 0.0720 (cottons)
= 0.0689 (filter paper)

Substituting these values of C_F, and the previously listed values for C_p and κ, the specialized forms of Equation 4.24 for each class of materials become:

Vinyls: R_o (cm/sec) = $(2.91 \times 10^{-3}) S^*/w_o$ (4.25a)
Nylons: R_o (cm/sec) = $(5.65 \times 10^{-4}) S^*/w_o$ (4.25b)
Sarans: R_o (cm/sec) = $(1.755 \times 10^{-3}) S^*/w_o$ (4.25c)
Carpets: R_o (cm/sec) = $(3.35 \times 10^{-4}) S^*/w_o$ (4.25d)
Cottons: R_o (cm/sec) = $(1.84 \times 10^{-3}) S^*/w_o$ (4.25e)
Filter papers: R_o (cm/sec) = $(1.56 \times 10^{-3}) S^*/w_o$ (4.25f)

Thus, for any particular material, if its weight per unit area and the slope of its ignition line at short ignition times ($S^* = H_a\sqrt{t}$) are known, the horizontal burning rate in the lengthwise normal direction can be predicted.

Since ignition data for the nylons which melted and dripped away from the ignition sample holder before ignition (N-15 through N-27) could not be obtained in the present version of the OURI ignition cabinet, the following procedure was used.

1. Assume that the calibration factor ($C_F = R_o\sqrt{t^*} = 0.0533$), derived from burning rate data on nylons N-1 through N-14, applies to nylons N-15 through N-27.
2. Using the burning rate data on N-15 through N-27, compute t^* for each nylon by Equation 4.22b.
3. From a plot of t^* versus H_a^* on logarithmetic coordinates for nylons N-1 through N-14 (a linear fit) read values of H_a^* corresponding to the t^* obtained in Item 2 above for each nylon, N-15 through N-27. (Some extrapolation of the linear plot was required since nylons N-15 through N-27 have lower values of t^* than nylons N-1 through N-14.)
4. Having obtained the values of t^* by Item 2 and H_a^* by Item 3, the slope ($S^* = H_a^*\sqrt{t^*}$) was computed for each nylon (N-15 through N-27).
5. From these values of S^* obtained in Item 4, the burning rate R_o was calculated for each nylon (N-15 through N-27) by Equation 4.25b.

The results of applying Equations 4.25 (a through f) to all of the vehicle interior materials are summarized in Figure 4.40. This graph compares the calculated or predicted burning rates against the experimentally measured burning rates. The straight line obtained by a least squares fit on the calculated results has a slope of 0.991; obviously if the calculated and experimental values were identical, the slope

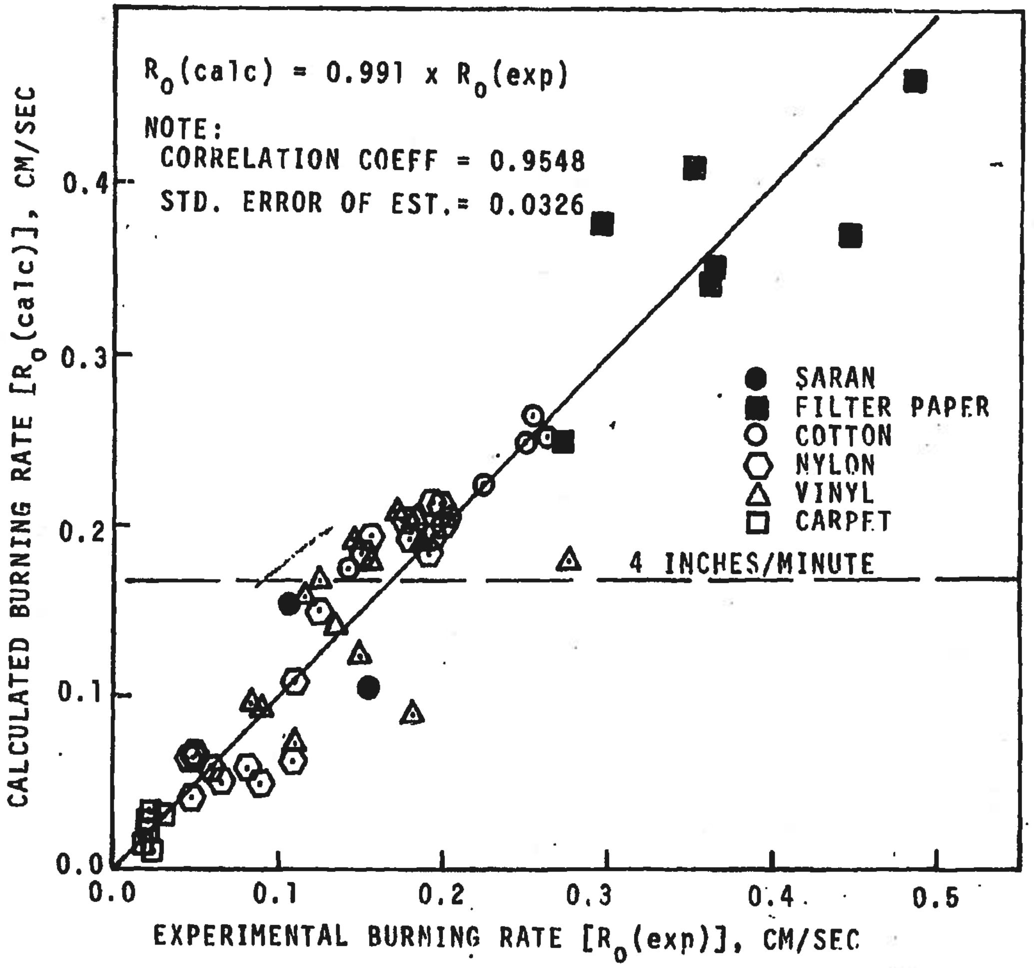


Figure 4.40. Comparison of calculated and experimental burning rates in the lengthwise-normal direction for all vehicle interior materials tested.

would have been 1.0. The correlation coefficient of 0.9548 and the standard error of estimate of 0.0326 indicates that Equations 4.25 are more than adequate for predicting burning rates of vehicle interior materials from ignition data (S*) and the weight per unit area (w_o) of the material.

4.2.7.4 Heat transfer rates in burning: The horizontal propagating heat flux, $\dot{q}_x$, of Figure 4.39e is the energy required to assure successive ignitions during the burning rate process. Thus, an energy balance per unit time on the burning sample can be expressed as

$$\dot{q}_x \, \delta Y = H_a{}^* \, t^* \, (R_o Y)$$

$$\text{or} \quad \dot{q}_x = [H_a{}^* \, t^* \cdot R_o]/\delta \qquad (4.26)$$

As stated before, the horizontal flux, $\dot{q}_x$, is the resultant of the two vertical fluxes $\dot{q}_y$ and $\dot{q}_y{}'$. Of particular interest in design for heating by direct contact with flame is the heat transfer rate between the flame and the object surrounded by the flame. For the burning test the average heat transfer rate per unit of area in contact with the flame is given by

$$(\dot{q})_{avg} = \frac{\dot{q}_y + \dot{q}_y{}'}{2} = \frac{\dot{q}_x}{2} \qquad (4.27)$$

Combining Equations 4.27 and 4.26

$$(\dot{q}_{avg}) = \frac{H_a{}^* \, t^* \, R_o}{2\delta} \qquad (4.28)$$

In the FMVSS 302 test once the sample is ignited, the Bunsen burner is removed; thereafter the sample must rely on its own heat of combustion to supply the ignition energy to the adjacent element just ahead of the flame front. Most of the heat of combustion is lost to the surroundings, and consequently only a small fraction of it is fed back to the sample. Unless this feedback is sufficient to induce successive ignitions, the flame will not propagate and will eventually die. Thus, even though a sample ignites when exposed to an <u>external</u> heating source, such as in the ignition test, there is no assurance that it will propagate a flame in the burning test since the external source (the Bunsen burner) is removed after ignition.

The feedback, F_B (cal/gm), is related to the propagating flux, $\dot{q}_x$, in the following manner:

$$F_B = \dot{q}_x/\rho R_o \tag{4.29}$$

The fraction of the heat of combustion, ΔH_c (cal/gm) that this feedback represents is

$$f_c = F_B/(\Delta H)_c \tag{4.30}$$

The heats of combustion for the various interior materials were determined in a standard bomb calorimeter:

Material	Heat of Combustion, cal/gm Range of Values	 Average Value
Vinyls	2744 - 5110	3592
Nylons	4683 - 7105	5724
Cottons	3554 - 4357	3856
Filter Papers	--	4500

Since the carpet samples were primarily nylon blends, the average heat of combustion for nylons was assumed to hold for the carpets. The wide range of values found for various samples of vinyls is probably due to the differences in plasticizer content and to the nature of the backing. The wide variation in the nylons probably reflects differences in blends with other materials such as rayons. The variation in the heat of combustion in cottons is probably more indicative of the reproducibility of the test procedure than a true variation in the cotton. The test procedure is specifically designed for granular materials, and considerable difficulties were encountered in using "fabric confetti."

The results of calculating $\dot{q}_x$, $(\dot{q})_{avg}$, F_B and f_c from Equations 4.26, 4.27, 4.29 and 4.30, respectively, are summarized in Table 4.6.

As can be seen the range of values for $(\dot{q})_{avg}$ extends between 0.22 cal/cm^2-sec (for some carpets) to as high as 4.82 cal/cm^2-sec for one of the nylons. However, over 65 percent of the computed values were below 3 cal/cm^2-sec. By way of comparison, total heat transfer measurements were made on burning pools of hydrocarbons and jet fuels up to 24 inches in diameter by inserting a specially designed, water-cooled metal probe into the flame. The maximum heat transfer to the probe was around 1.3 cal/cm^2-sec; the predominant mode of heat transfer was by radiation. The maximum that has ever been observed in this type of measurement is on the order of 3 cal/cm^2-sec. However, in some petroleum cracking furnaces, rates as high as 5 cal/cm^2-sec have been reported. Intuitively, a metal inserted into a flame would not be expected to experience as high heat transfer rates as a burning specimen. In the latter case, the flame underneath the specimen adheres to the surface, and the flame above the surface appears to do likewise for most of the samples tested. The direct flame contact with the surface eliminates any possibilities for a stagnant boundary layer between the flame and surface which could constitute a high resistance to heat transfer.

The horizontal propagating flux, $\dot{q}_x$, ranges between 0.5 cal/cm^2-sec and about 15 cal/cm^2-sec with most of the values falling below 5 cal/cm^2-sec.

Despite these high heat fluxes, the amount of heat energy that is fed back from the flame to the sample is under 200 cal/gm of material burned; in fact, for at least 75 percent

TABLE 4.6

SUMMARY OF HEAT TRANSFER ANALYSES ON BURNING SAMPLES

Material	$\dot{q}_x = R_o H_a^* t^* / \delta$	$(\dot{q})_{avg} = \dot{q}R/2$	Feedback $F_B = \dot{q}_x / \rho R_o$	Fraction $f_c = F_B / \Delta H_c$
V-1	1.693	0.85	27.20	0.00757
V-2	2.573	1.26	25.91	0.00721
V-3	1.506	0.75	20.28	0.00565
V-4	2.155	1.08	31.17	0.00868
V-5	2.256	1.13	16.00	0.00445
V-6	4.445	2.22	34.79	0.00968
V-7	3.630	1.82	30.92	0.00861
V-8	4.887	2.44	31.59	0.00879
V-9	3.798	1.90	36.33	0.01011
V-10	3.360	1.68	33.40	0.00930
V-11	4.401	2.20	30.05	0.00837
V-12	4.516	2.26	33.03	0.00920
V-13	4.412	2.21	31.63	0.00880
V-15	5.800	2.90	20.09	0.00559
N-1	2.86	1.43	56.21	0.00982
N-4	2.86	1.43	66.29	0.01158
N-5	1.880	0.94	108.26	0.01891
N-7	1.553	0.78	95.46	0.01668
N-8	3.302	1.65	126.2	0.02205
N-9	2.926	1.46	91.86	0.01605
N-10	2.961	1.48	115.7	0.02021
N-11	3.096	1.55	117.8	0.0206
N-12	3.130	1.56	113.8	0.01988
N-13	2.151	1.08	62.96	0.01100
N-14	2.591	1.29	77.73	0.01358
N-15	9.05	4.52	45.51	0.01669
N-16	5.07	2.64	114.14	0.01994
N-17	7.93	3.97	118.6	0.02072
N-18	9.37	4.68	94.87	0.01658
N-19	9.64	4.82	100.95	0.01763
N-20	6.82	3.41	63.56	0.01110
N-21	10.35	5.18	103.26	0.01804
N-22	9.83	4.91	106.08	0.01853
N-23	9.31	4.66	119.7	0.0296
N-25	5.07	2.54	160.9	0.0281
N-26	8.50	4.25	106.1	0.0185
N-27	8.58	4.29	111.9	0.01955

TABLE 4.6--Continued

Material	$\dot{q}_x = R_o H_a^* t^*/\delta$	$(\dot{q})_{avg} = \dot{q}R/2$	Feedback $F_B = \dot{q}_x/\rho R_o$	Fraction $f_c = F_B/\Delta H_c$
CT-1	3.449	1.72	45.30	0.01175
CT-2	4.537	2.27	39.71	0.01030
CT-3	4.802	2.40	38.45	0.0100
CT-5	5.378	2.69	37.33	0.00970
CT-6	5.540	2.77	39.73	0.0103
CT-7	5.010	2.05	35.36	0.00917
FP-1	6.851	3.42	43.13	0.00958
FP-2	5.290	2.64	41.23	0.00916
FP-3	6.860	3.43	53.03	0.0118
FP-4	8.751	4.38	42.91	0.00954
FP-5	8.135	4.07	49.45	0.0110
FP-6	8.483	4.24	38.99	0.00866
FP-7	15.237	7.62	42.38	0.00942
C-1	0.6247	0.31	160.0	0.0280
C-2	--	--	--	--
C-3	0.4427	0.22	123.42	0.0216
C-4	0.5656	0.29	129.9	0.0227
C-5	--	--	--	--
C-6	0.6444	0.32	171.38	0.0299
C-7	0.5927	0.30	158.3	0.0277
C-8	0.4934	0.25	83.43	0.0146
C-9	0.6115	0.31	114.60	0.0200
S-3	1.631	0.82	31.15	--
S-4	2.285	1.19	55.27	--

of the materials the feedback is under 100 cal/gm. This amount of feedback represents less than 2 percent of the heat of combustion; the remaining 98 percent represents heat losses to the surroundings. These percentages are in general agreement with observations on burning liquid pools.

4.2.8 Conclusions and Recommendations

Based on the results of about 2000 burning rate tests on vehicle interior materials, the following conclusions are drawn:

1. There is an adequate selection of materials (pre 1971) to outfit a vehicle interior completely which will have an average burning rate in the lengthwise-normal direction of under 4 inches/minute in the FMVSS 302 test.
2. The FMVSS 302 test has a basic reproducibility of at least 10 percent, and possibly 5 percent of the standard deviation from the average burning rate. Higher deviations from the mean are due primarily to non-uniformities in the manufacture of the material itself, and they do not appear to be strongly dependent on the type of material nor its burning rate.
3. The principal merit in the FMVSS 302 standard lies in its inherent requirement for uniformity in the manufacture of the material and as a useful device for preliminary screening of relative flammability of materials.
4. The limit of 4 inches/minute in the FMVSS 302 standard is purely arbitrary since the burning rate for a particular material can vary over two orders of magnitude depending on the test apparatus and procedure, angle of inclination of the burning, wind, width of specimen, presence of external heating from adjacent fires, orientation of the fibers, etc.
5. The burning rates of materials can be predicted if the calibration factors for the test apparatus, the thermal

properties and physical dimensions of the sample, and the ignition characteristics are known. The calibration factors for the FMVSS 302 test and the ignition characteristics have been established for a wide variety of interior materials so that it should now be possible to predict FMVSS burning rates in the lengthwise-normal direction without running the burning test although knowledge of the ignition characteristics would still be required.

6. Since the burning rate varies directly with the slope of the ignition curve and inversely with the weight per unit area of the material, a criterion exists for the manufacture of materials to meet prescribed burning rates.
7. The burning process is basically understood and well-behaved in the sense that it is amenable to theoretical analyses.

Based on these findings, recommendations for additional work are suggested:

1. Calibration factors for burning rates in the FMVSS 302 standard for orientations of the fiber other than in the lengthwise-normal direction need to be established. It is conceivable that some averaging scheme for the burning rates in all orientations can be developed which would be more indicative of the general flammability of the materials.
2. Other burning test apparatuses and procedures should be investigated to determine whether a simple and predictable relationship exists among them. Simultaneously, it is conceivable that a burning rate test which is more representative of vehicle interior fires would become apparent.
3. Burning rate tests should be run on the individual fibers and formulating compounds to determine how they influence the burning rate characteristics of the final product.
4. The possibility of capitalizing on weave or decorative patterns and on discontinuities built into the material

for reducing burning rates needs to be investigated.

5. Although the basic reproducibility of the FMVSS 302 test procedure is on the order of a 5 to 10 percent deviation from the mean burning rate, there is no assurance that a single test on a particular material might pass the standard, whereas all subsequent tests would fail, or vice versa. Therefore, consideration should be given to a standard that allows any material to pass which has an arithmetic average burning rate of less than the prescribed limit and a percent deviation from the average burning rate of less than 10 percent based on a minimum of 10 burning rate tests.
6. The significance of the presently prescribed burning rate limit of 4 inches/minute requires further analysis and review.

4.3 AUTOMOBILE INTERIOR FIRES

A previous investigation of life hazards associated with fires in vehicle interior was limited to gasoline fires confined in a metal pan (4). The primary objective in these studies was to investigate the changes in temperature and gas composition as a function of time and position rather than to simulate a realistic vehicle fire. Under the present contract, No. FH-11-7512, more realistic test conditions, such as burning seats and interiors, were employed to investigate the time and position dependency of temperature, gas composition and smoke density and to assess the hazard potentials in vehicle fires.

The previous tests revealed that gas concentrations in the interior are approximately independent of position, that CO (carbon monoxide) concentrations never exceed 0.5 percent and that O_2 (oxygen) concentrations are always greater than 12 percent when burning small, confined gasoline fires. These findings, combined with conjectures that a lethal atmosphere for the time period involved must contain more than 1.25 percent CO or less than 10 percent O_2 (18), indicated that excess CO or lack of O_2 will not control survival times if there are small gasoline fires in automobiles (4).

These earlier test procedures were refined under this contract by installing equipment for continuous monitoring of CO and O_2 concentrations, and the scope of the tests was expanded to include burning of vehicle interior materials such as seats and headliners under completely enclosed and free-ventilation conditions. In addition, during the present tests, individual gas samples were analyzed for NO_2 (nitrogen dioxide), SO_2 (sulfur dioxide), HCN (hydrogen cyanide), CO (carbon monoxide), CO_2 (carbon monoxide), HCl (hydrogen chloride), $COCl_2$ (phosgene) and vinyl chloride to detect any presence of these hazardous gases.

Since qualitative observations during the previous tests indicated that excessive smoke from the interior fires could be a serious life hazard, equipment was installed for continuous recording of the smoke density. Aside from obscuring vision, which is a critical parameter in occupant escape, smoke posed hazards from the standpoint of toxicity and irritation to the eyes, throat and lungs. Unfortunately, no facilities were available for measuring physiological and psychological responses to smoke. Therefore, the quantitative data on hazards related to smoke were limited to measurements of light attenuation which indicates smoke density and relates to obscured vision.

Temperature at various positions inside the passenger compartment and on the outside body of the passenger compartment were measured to ascertain not only if dangerously high temperatures result from the fires but also to determine if the results from different tests could be correlated.

Although these vehicle interior fire tests constituted the most cost-intensive and potentially-hazardous undertakings during this contract, they were well worth the effort. A much better understanding of the life hazards associated with vehicle interior fires has been acquired. Qualitative and quantitative results from these experiments revealed the relative importance of the various fire-related factors affecting occupant survival. Rough estimates of the circumstances leading to hazardous conditions can also be gleaned from the information presented herein.

4.3.1 Equipment and Procedures

A 1952 Dodge Meadowbrook four-door sedan was equipped with instruments as detailed previously (4). The instrumentation for the previous tests provided for measurement of air temperature at six locations in the car, for continuous measurement of the amount of fuel consumed, and for continuous measurement of CO and O_2 concentrations. Three additional thermocouples were attached to the metal body on the outside of the vehicle. The locations of these sampling ports and thermocouples are identified in Figure 4.41. More detailed information on the sampling probes is given in Table 4.7.

TABLE 4.7

LOCATIONS OF SAMPLING PROBES

Probe	Distance from Ceiling (C) or Floor (F) Inches	Distance from Side of Passenger Compartment (A in Figure 4.41) Inches	Distance from Base of Back of Front Seat (F) or Back Seat (B) (B in Figure 4.41) Inches
1	12 (C)	13	2 (F)
2	9 (C)	13	2 (F)
3	12 (C)	12	9 (B)
4	12 (C)	12	8 (B)
5	12 (F)	24	29 1/2 (B)
6	24 (F)	6	28 (B)

4.3.1.1 <u>Smoke density</u>: Apparatus to measure smoke density by changes in light transmission was added. This apparatus consisted of two photocells used in conjunction with two light sources. One photocell was 7.5 inches from its light source and the other was 13.5 inches from its light source. Changes in resistance due to smoke were converted to voltages and were recorded continuously.

4.3.1.2 <u>Fuel consumption</u>: The fuel-weighing apparatus used previously was not applicable to these tests because the fuel in the present tests was an actual seat instead of gasoline confined in a metal pan. Accordingly, a new weighing

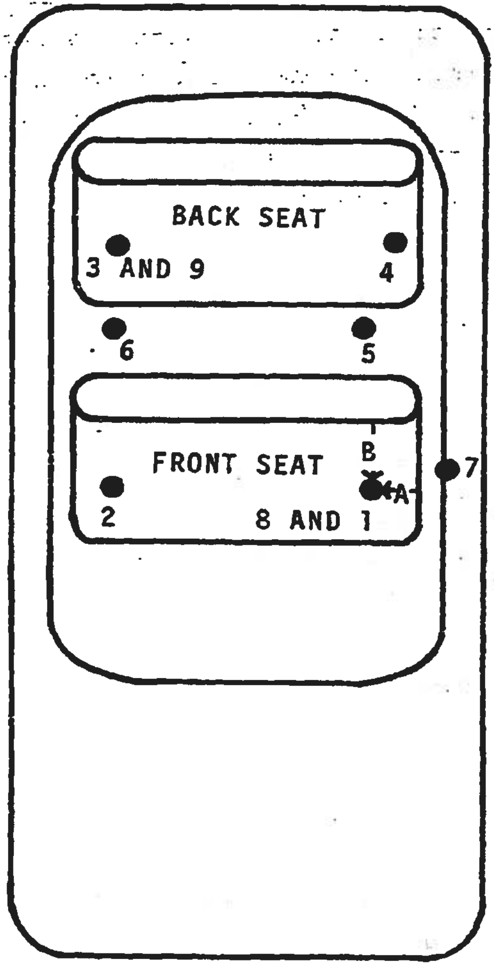


Figure 4.41. Locations of sampling ports (1 through 6) and thermocouples (1 through 9). NOTE: Locations 7, 8 and 9 are on the exterior of the passenger compartment.

system was built. The seat to be burned was suspended by three wires which were hooked together and attached to a weighing sling as shown in Figure 4.42. The weight of the seat was carried by two large springs (S in the figure) and changes in weight of the seat (which caused minute changes in extension of the springs) was detected by a displacement transducer (T in Figure 4.42). The output of the transducer was continuously measured on a recorder. An adjustment screw (A in Figure 4.42) allowed compensation for differing weights between seats. The sling was securely anchored above the chamber in which the car was burned.

The weighing apparatus was calibrated before each test by placing known weights on the seat.

4.3.1.3 Temperature measurement: In addition to the six thermocouples used previously, three thermocouples were attached to the outside of the passenger compartment body to allow continuous measurement of the body temperature. Two of these thermocouples were on the outside of the roof (8 and 9 in Figure 4.41), where the hottest temperatures were expected, and one was on the driver's side front door (7 in Figure 4.41).

4.3.1.4 Gas sampling: Previously, a vacuum line was connected through a manifold to each sampling port to allow continuous sampling of gas from a specific location in the automobile interior. This system was used for continuous measurement of O_2 and CO concentrations during the present tests.

Another vacuum pump and appropriate valves were connected to the manifold to allow an additional, discrete gas sample to be obtained during the present tests. This discrete gas sample was taken when the O_2 concentration (indicated by the continuous analyzer) was at a minimum, so that the concentrations of toxic gases in the sample were probably maximum values. This sample was analyzed to measure concentrations

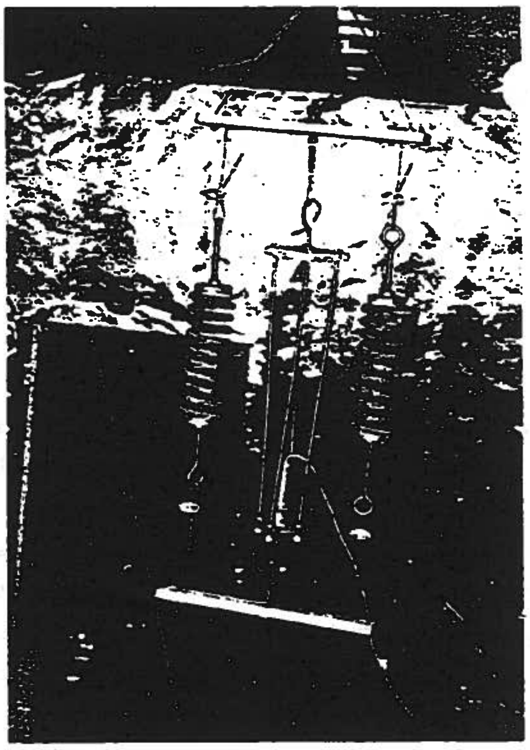


Figure 4.42. Sling for supporting and weighing the burning seats.

of the following gases in the car: vinyl chloride, phosgene, sulfur dioxide, hydrogen cyanide, carbon dioxide, carbon monoxide, nitrogen dioxide and hydrogen chloride.

The continuous analysis for O_2 and CO was performed using paramagnetic and infrared analyzers, as described in the report on Contract FH-11-7303 (4). The discrete samples were analyzed using a Unico No. 400 Gas Detector Kit and Gas Detector Tubes. This technique is less accurate and less reliable than instrumental techniques because it involves a colorimetric determination utilizing solid chemical reagents. The scope and funding under this contract (FH-11-7512) did not provide for more reliable and sophisticated analytical techniques.

4.3.2 Discussion of Results

Detailed discussions relating to smoke densities, gas concentrations and temperatures measured in the passenger compartment are presented in this section. In addition, some qualitative observations are reported.

Individual experiments were performed under several conditions to assess differences caused by ventilation and by ignition on or beneath the seat. Table 4.8 summarizes the seat materials, method of ignition and other conditions relating to the tests. Since experimental techniques were checked and refined throughout tests 1-6, these data are not included in Table 4.8.

4.3.2.1 Qualitative physiological responses to interior fires: On several occasions, when test personnel had to enter the passenger compartment to service instrumentation shortly after visible burning stopped, they experienced severe gagging or an inability to inhale. Although the cause of this bronchospasm was not identified, it is obvious that it poses a severe hazard to occupants.

TABLE 4.8

SEAT MATERIALS AND METHODS OF IGNITION

Test	Seat	Seat Material*	Ignition Method**	Comments
7	'70 Impala	V	2 cc acetone on seat	
8	'70 Mustang	V	1 cc acetone on seat	
9	Urethane foam mock-up		1 cc acetone on seat	
10	Rubber Latex foam mock-up		1 cc acetone on seat	
11	Aborted test			
12	'69 Charger	V	1 cc acetone on seat	Weighing system malfunction
13	'68 Rambler	V	1 cc acetone on seat	
14	'68 Plymouth	N	1 cc acetone on seat	Temperature recorder malfunction
15	GM	V	1 cc acetone on seat	Gas sampling malfunction for 1st 6 min
16	'69 Ford	V	1 cc acetone on seat	
17	'69 Impala	V	1 cc acetone on seat	
18	GM	V	1 cc acetone on seat	
19	'67 Dodge	N	1 cc acetone on seat	
20	?	N	1 cc acetone on seat	
21	'70 Superbee	V	70 cc gasoline under seat	Faulty ignition
22	'70 Superbee	V	70 cc gasoline under seat	Repeat of #21
23	?	V	70 cc gasoline under seat	

*N = Nylon; V = Vinyl

**When 1 or 2 cc of acetone were needed for ignition, the acetone was distributed on 5 methenamine tablets.

TABLE 4.8--Continued

Test	Seat	Seat Material*	Ignition Method**	Comments
24	GM Pickup	N	70 cc gasoline under seat	Gas sampling port plugged
25	?	N+V	70 cc gasoline under seat	
26	'67 Torino	V	6 cc gasoline on seat	
27	Aborted test			
28	'69 Pontiac	N	70 cc gasoline under seat	
29	'69 Chevelle	V	5.5 cc gasoline on seat	Weighing system malfunction
30	'69 Chevelle	V	70 cc gasoline under seat	
31	'69 Chevelle	V	70 cc gasoline on seat	Door open during test
32	'71 Buick LeSabre	V	40 cc gasoline on seat	Door open during test; movies taken
33	'71 Olds	V+N	70 cc gasoline on seat	Door open during test; movies taken

*N = Nylon; V = Vinyl.

**When 1 or 2 cc of acetone were needed for ignition, the acetone was distributed on 5 methenamine tablets.

Test personnel invariably complained of headaches, raw throats and sinus inflammations even if they did not enter the vehicle. Thus, aside from the burn hazards discussed in Subsection 4.1.4, the environment in and near the burning vehicle constitutes a serious threat to passengers and attendees.

4.3.2.2 Nature of interior fires: Two classes of fires were investigated: (1) the calm fire in which all windows and doors remained closed so that the air supply was limited and eventually depleted, and (2) the wind-driven fire in which the right front door remained open until the fire became so intense that it threatened to destroy the test enclosure.

For the vehicle interior fire tests in which the passenger compartment was completely closed, the nature of the burning was similar to that observed under the previous contract (4). Ignition was followed by a relatively large fire which quickly consumed the fuel used to start the fire. The flame quickly subsided to a small, slowly burning fire as the seat cover and seat material began to burn. The intensity was too low to ignite any other interior materials, such as the headliner or door panels. However, it continued to smolder for hours after visible burning ceased and would enflame again if fresh air was admitted to the interior. This type of fire presents a hazard only to occupants who are immobilized either by entrapment or unconsciousness.

Three tests involving ignition on the front seat were run with the right front door open. (Movies were taken during two of these tests.) The fire behavior during the first minute in all of these tests resembled the tests in which the door remained closed. However, after 2 to 3 minutes the fire increased in intensity and spread up the seat back. Finally, after 3 to 5 min the seat began to burn vigorously. Next, the headliner burst into flames and the entire passenger compartment was immediately engulfed in flames. (This sudden transition from a localized fire to a fire which covers a far greater area is called flash-over.) Flames several feet high extended out of the open door. Eventually, the door had to be closed to confine the fire since the test chamber was on the verge of total destruction. A stratified layer of smoke was visible inside the car throughout the tests (it is clearly visible in the movies). The 3/32-inch steel cable which supported the seat broke soon after the headliner ignited; paint on the roof blistered and the windows cracked, but did not break. (All windows in the test vehicle were of the laminated glass variety.) Needless to say, the fire hazard to occupants is extreme under these conditions which develop within 2 to 3 minutes after ignition and become full-blown within 3 to 5 minutes.

The contrast between the relatively calm fire observed in an enclosed compartment and the vigorous fire, with resultant flash-over, observed when the compartment is open is graphically illustrated by Figures 4.43 and 4.44.

Figure 4.43 shows the time dependence of pertinent parameters such as temperature rise and gas composition for one test in which the passenger-side front door remained open. Figure 4.44 indicates the time dependence of these parameters when the interior remained closed to the outside for the duration of the test.

These figures clearly demonstrate that the magnitudes of weight loss and temperature rise were much greater when a door remained open. For instance, after four minutes of burning the temperature and weight loss were 700°F and 425 grams, respectively, for the open-door case, in contrast to 225°F and 80 grams for the case when the interior was totally enclosed. The maximum burning rates for the open-door case occurred between 3.25 and 3.75 minutes; 280 grams in 0.5 minutes or 560 gm/min. For the closed door case, the maximum

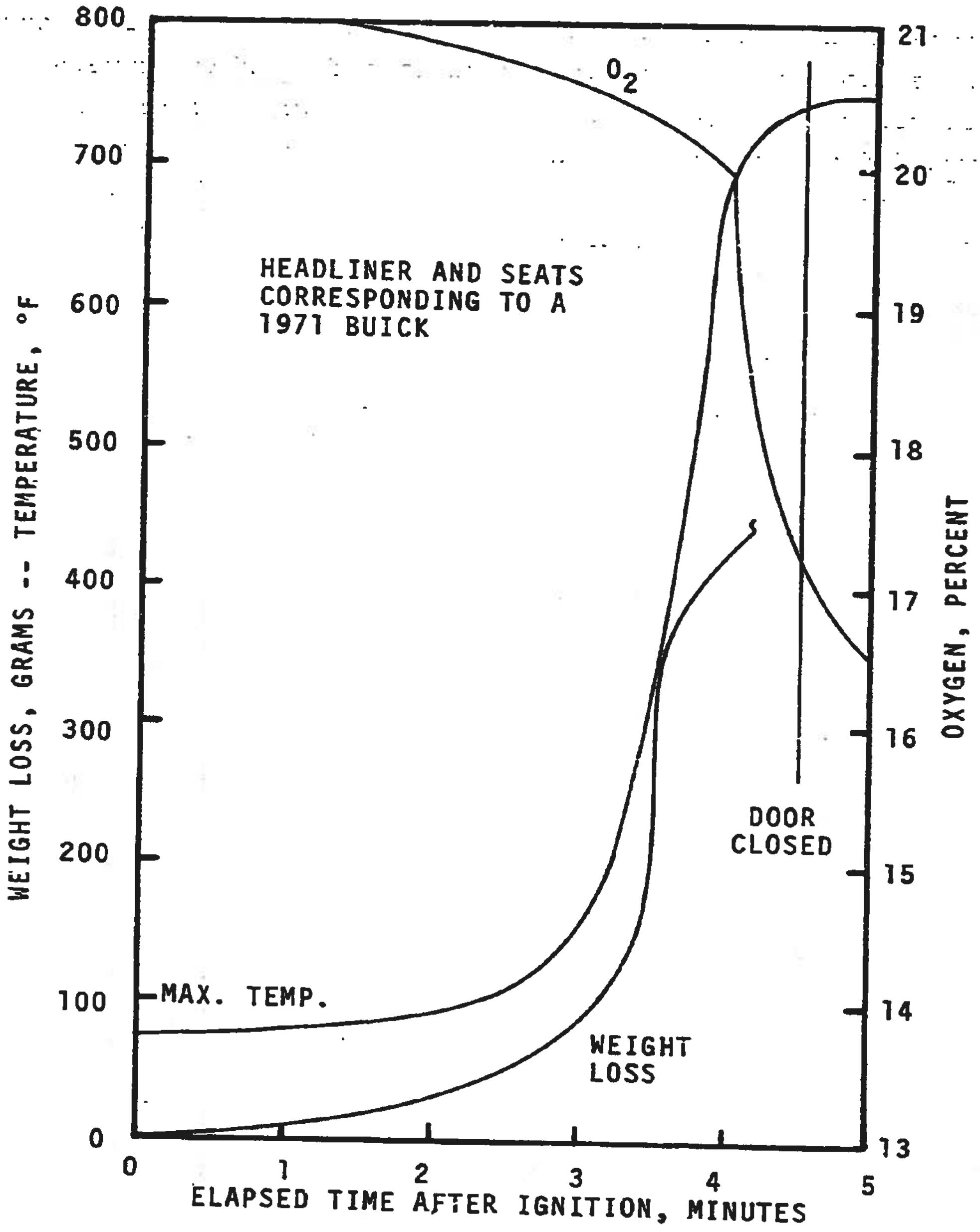


Figure 4.43. The changes in maximum interior temperature and gas composition during the progress of a vehicle fire with one door open.

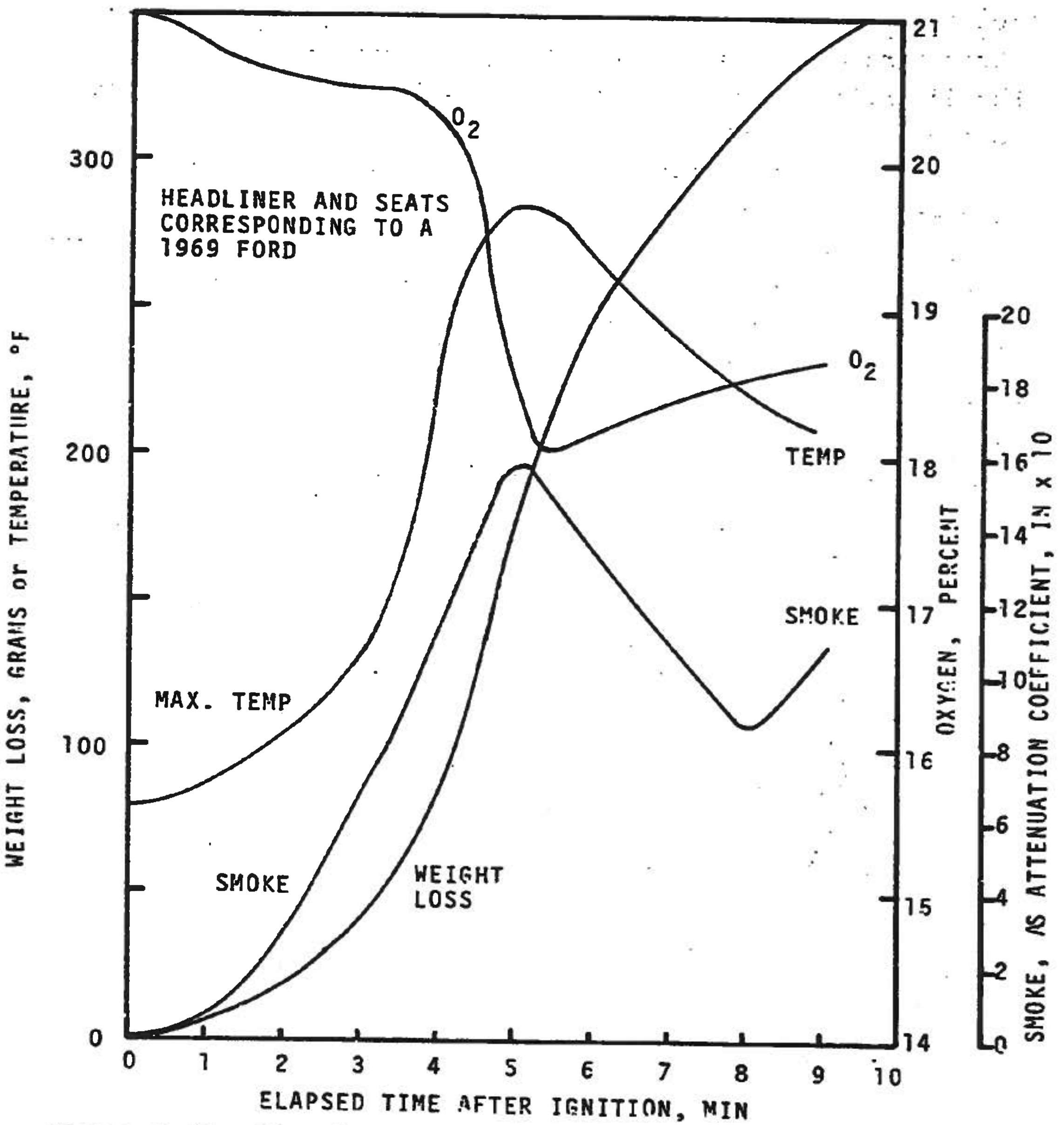


Figure 4.44. The changes in maximum interior temperature and gas composition during the progress of a vehicle fire with all windows and doors closed.

burning rate was observed between 4.5 and 5.5 minutes after the fire was started: 87 grams in one minute. The phenomenon of flash-over, mentioned earlier in this section, is clearly revealed in Figure 4.43 by the dramatic increases in burning rate and temperature after 3.25 minutes had elapsed following ignition.

These two figures compare the scale of the fires encountered in the open-door and closed door situations. In the three open-door tests, it is significant to note that the elapsed times at which maximum temperatures, burning rates, flash-overs and smoke densities occurred were quite similar. In other words, within 3 to 5 minutes after a fire starts in a vehicle with a door (or window) open, the probability that the entire interior will become involved is very high. On the other hand, the closed door tests showed considerable variability. For example, the elapsed time to reach a critical smoke density (defined later in Subsection 4.3.2.4) varied from 2 to 17 minutes in the closed door case. Consequently Figure 4.44 is illustrative but not typical.

The rate of weight loss measurements provides a means for making "ballpark" estimates of the heat release rates and average linear burning rates. In the following, the dimensions of the front seat were taken as 20 inches by 50 inches, of the front seat back, 20 inches by 50 inches, and of the headliner, 50 inches by 80 inches. The heat of combustion of vinyl was taken as 4500 cal/gm (see Subsection 4.2.7.4). The average weight of vinyl was assumed to be 25 oz/yd^2, and the weight of vinyl plus foam padding with supporting fabric was taken as 50 oz/yd^2.

1. Closed Door Case. Only the seat which was ignited by the acetone and methenamine tablets burned; the headliner did not ignite. A strip about 10 inches wide was burned across the seat and up the back. Only the vinyl surface layer burned; the foam padding did not.

a. Maximum weight loss rate = 87 gm/min

b. Heat release rate = 4500 x 87 = 400,000 cal/min

c. Original surface area of vinyl on seat and seat back = 2(20 x 50) = 2000 in^2

d. Mass of vinyl = 2000 in^2 @ 25 oz/yd^2 = 1090 gm

e. Fraction of seat and seat back burned in <u>one minute</u> = 87/1090 = 0.08

f. Area of seat and back burned = 0.08 (2000) = 160 in^2/minute

g. Average linear burning rate for seat and back (10-inch strip) = R = 160/10 = 16 inches/minute

h. Average horizontal burning rate of vinyls (see Section 4.2) = 3.5 inches/minute

i. Average inclined (75°) burning rate of vinyls (see Figure 4.26) = 30 inches/minute

j. Average of horizontal and inclined burning rates = (3.5 + 30)(1/2) = 17 inches/minute.

The use of the average in Item j is defensible since it covers the period of 4.5 to 5.0 minutes, and according to Figure 4.44 significant weight loss continues to occur after this time. Presumably the 10-inch strip on the seat back is consumed during this maximum rate period, and thereafter the seat continues to burn.

2. Open door case. The seat and seat back burned through the surface layer and padding down to the springs, again in a strip about 10 inches wide. The fact that the same width of strip was burned in both the closed- and open-door cases reflects the similarity in the ignition procedures. It also indicates that the seat and back do not have a tendency to burn in the transverse direction (see Subsection 4.2.6.2). Most of the weight loss occurred during a one-half minute interval at a rate of 560 gm/min. The headliner was completely burned in about 27 seconds (as determined from the movies); 4000 in^2 at 25 oz/yd^2 = 2180 gm in 27 sec.

a. Maximum weight loss rate in seat assembly = 560 gm/min

b. Heat released in 30 <u>seconds</u>:

Seat and back 4500 (560) = 2.5×10^6

Headliner 4500 (2180) = $\underline{9.8 \times 10^6}$

12.3×10^6

cal/minute = $12.3 \times 10^6 \times 2 = 25 \times 10^6$

c. Initial weight of vinyl plus padding on seat and back = 2000 in^2 @ 50 oz/yd^2 = 2200 gm

d. Fraction of seat and back burned in 30 seconds: 560(1/2)/2200 = 0.127

e. Area of seat and back burned in 30 seconds = 0.127(2000) ≈ 250 in^2

f. Length burned in 30 seconds (strip 10-inches wide) = 250/10 = 25 inches in 30 seconds = 50 inches in 1 min

g. Wind factor for open door--according to Figure 4.32, a wind velocity of 2 miles/hr increases the burning rate of vinyls by a factor of at least 3 over the no-wind rate. Since the no-wind rate was estimated to be 17 inches/minute in the closed-door case (see Item j above) then 17 x 3 = 51 inches/minute. Compare with Item f, 50 inches/minute.

3. Headliner-Open Door Case

a. Observed burning rate 80 inches/27 sec = 178 inches/min

b. The vinyl headliner is preheated by the convective column of gases rising from the burning seat and back. Based on experience with hydrocarbon fires, about 70 percent of the heat of combustion is in this convective column. Thus, 0.70 $(2.5 \times 10^6) = 1.75 \times 10^6$ cal in 30 sec = 58,500 cal/sec.

c. The area of the column is taken to be the 10-inch wide burning strip and the 30-inch depth of the seat or 200 in^2 = 1300 cm^2

d. Flux rate to headliner = 58500/1300 = 45 cal/cm^2-sec

e. The average propagating flux, q_x, for burning vinyls is, according to Table 4.7, = 3.53 cal/cm^2-sec

f. Therefore the total propagating flux is 45 + 3.53 = 48.53 cal/cm^2-sec. According to Equation 4.26, the horizontal burning rate is directly proportional to the propagating flux.

g. The correction factor for width from Figure 4.36 (for a 10-inch width) = 4.56/3.97 = 1.15. It is visualized that the headliner burns lengthwise (front-to-back) in a 10-inch strip along the center and simultaneously crosswise to each side. See Subsection 4.2.6.2.

h. Therefore the predicted horizontal burning rate is R_o (flux factor)(wind factor)(width factor) = 3.5 (48.53/3.53)(3)(1.15) = 166 inches/minute

i. Compare with Item a for which the observed rate = 178 inches/minute.

The almost unbelievable agreement between the results observed in these two vehicle interior fire tests and the predictions based on the laboratory burning tests discussed in Section 4.2 does not warrant sweeping generalizations. It does, however, demonstrate that the predictability of fire behavior in vehicle interiors is not hopeless and that the FMVSS 302 test procedure is not irrelevant.

4.3.2.3 Gas concentration analysis: Table 4.9 summarizes maximum CO and minimum O_2 concentrations observed by continuous monitoring. (Continuous monitoring of CO was impossible for runs 25 through 32 because the CO equipment was being repaired.) Concentrations of CO, CO_2 and vinyl chloride obtained from single colorimetric measurements are also listed in Table 4.9

HCN, HCl and phosgene were never detected by the colorimetric tubes. Traces of NO_2 and SO_2 were, however, found during burning of the mock-up seats.

TABLE 4.9

SUMMARY OF GAS CONCENTRATIONS THAT AFFECT LIFE

(Runs 7 through 31 are closed door;
runs 32 and 33 are open door)

Test	Seat	Min O_2 (%)	Max CO[a] (%)	CO[b] (%)	CO_2[b] (%)	Vinyl Chloride[b] (%)
7	'70 Impala	18.0	0.67		3.2	0.1
8	'70 Mustang	15.8	0.80		3.3	0.05
9*	Urethane foam mock-up	8.2	1.20		10.4	0.45
10**	Rubber latex foam mock-up	8.8	1.05		5.4	0.1
11	Test aborted					
12	'69 Charger	19.0	0.45		2.0	0.05
13	'68 Rambler	16.8	0.68		4.0	0.05
14	'68 Plymouth	18.8	0.50		1.25	0.05
15	GM	17.2	0.72	0.72	10.4	
16	'69 Ford	17.0	0.58	0.36	0.12	0.05
17	'69 Impala	19.0	0.40	0.30	2.0	0.05
18	GM	18.0	0.60	0.60	2.8	0.05
19	'67 Dodge	19.8	0.32	0.05	0.8	0.05
20***	?	19.5	0.38	0.10	3.4	0.05
21***	Test aborted					
22***	'70 Superbee	18.0	0.62	0.70	5.8	0.1

[a] Data from continuous infrared analyzer.

[b] Data from colorimetric analysis.

*5 ppm SO_2 and 5 ppm NO_2 measured during this test.

**5 ppm SO_2 and 100 ppm NO_2 measured during this test.

***Ignition from beneath seat.

TABLE 4.9--Continued

Test	Seat	Min O_2 (%)	Max CO[a] (%)	CO[b] (%)	CO_2[b] (%)	Vinyl Chloride[b] (%)
23***	?	20.0	0.32	0.36	3.2	
24***	No gas samples obtained					
25***	?	18.0		0.70		0.06
26	'67 Torino	20.0		0.36		0.06
27	Test aborted					
28***	'69 Pontiac	19.8		0.70		0.05
29	'60 Chevelle	20.0		0.17		0.05
30***	'69 Chevelle	18.0		0.60		0.05
31	'69 Chevelle	16.8				
32	'71 Buick LeSabre	16.5				
33	'71 Olds Cutlass	No gas samples taken				

[a] Data from continuous infrared analyzer.

[b] Data from colorimetric analysis.

***Ignition from beneath seat.

Except for tests 19 and 20, the continuous and colorimetric measurements of CO for each test corroborate each other and thus support the validity of the results. The disagreement indicated for tests 19 and 20 is unexplainable; it could have been caused by incorrect sampling procedures for the colorimetric sample. The maximum concentrations of toxic gases and maximum oxygen depletion data in Table 4.9 agree with previous results obtained by burning hydrocarbons and gasoline in enclosed spaces (4, 19, 20) and thus further support the validity of the results. Much higher concentrations of toxic gases and much greater oxygen depletion have been observed when rubber, wool or silk were burned in enclosed spaces (20).

The concentration of vinyl chloride was almost always less than 0.05 percent which is the lower limit of sensitivity of the technique.

The data on minimum oxygen concentration in Table 4.9 indicate that the oxygen concentration is rarely less than 16 percent; usually the minimum is as high as 18 to 20 percent. These minimum oxygen concentrations are even higher than the lowest concentration (12 percent) observed during previous tests (4) in which only gasoline was burned in the interior. The exceptions to the generalization that oxygen concentrations exceeded 16 percent were observed during burning of the two foam mock-up seats and a vinyl seat from a 1970 Mustang.

It should be emphasized that only relatively small fires, started by ignition of small amounts of fuel, were used in these tests. Consequently, oxygen concentrations well below 16 percent would very likely occur in large fires or in cases when large amounts of rubber, wool or silk are burned (20). Of course, the fire itself, and not the lack of oxygen, constitutes the primary life hazard in large fires (see Subsection 4.1.4).

Data presented in Table 4.9 also indicate that burning the foam mock-up seats produced a much more hazardous environment than burning normal seats. During burning of the foam mock-ups, oxygen concentrations were significantly lower (below the suggested lower limit of 10 percent for life support), while CO, CO_2 and vinyl chloride concentrations were significantly higher. Although these tests alone are not conclusive, they do suggest that the foams may present a significant hazard in fire situations.

Previous results from burning gasoline in pans inside the car (4) indicated that oxygen and CO concentrations were independent of position and could be related by equations of the form:

$$c_{CO} = A\delta^a \qquad (4.31)$$

$$(21 - c_{O_2}) = B\delta^b \qquad (4.32)$$

where $\delta = m(t)/\rho V_r$ is the ratio of the mass of fuel burned as a function of time, $m(t)$, to the mass of air originally in the enclosed space. A, B, a and b are constants.

Equations 4.31 and 4.32 are only applicable when the dependent variable (c_{CO} or $21 - c_{O_2}$) is increasing with the amount of fuel burned.

The variable δ used in Equations 4.31 and 4.32 must be modified to account for differences in the stoichiometry of the combustion reactions if results from fuels other than gasoline (such as seat covers) are to be compared with results from tests in which gasoline was the fuel.

For instance, the reactions for the complete combustion of octane (used to approximate the combustion of gasoline) and the fundamental chemical species being burned in vinyl seat covers are:

$$C_8H_{18} + 12\tfrac{1}{2}\, O_2 \rightarrow 8CO_2 + 9H_2O \qquad (4.33)$$

$$C_2H_3Cl + 2\frac{1}{2} O_2 \rightarrow 2CO_2 + H_2O + HCl \qquad (4.34)$$

The vinyl monomer is used in the equation to estimate the oxygen requirements. Oxygen requirements per gram will be little different for the polymer. Use of Equations 4.33 and 4.34 together with appropriate molecular weights indicates that combustion of 1 gram of octane consumes 0.12 mol of O_2 while combustion of 1 gram of vinyl would consume only 0.032 mol of O_2. Therefore, the oxygen depletion relations, which are based on the mass of fuel burned (Equation 4-32) for these two fuels could not be expected to coincide. A factor, γ, the ratio of the theoretical number of mols of O_2 consumed by complete combustion of one gram of a given material to the number of mols of O_2 consumed by complete combustion of one gram of octane was used to put all fuels on a common basis for Equation 4.32. Thus Equation 4.32 becomes:

$$(21 - c_{O_2}) = B(\gamma\delta)^b \qquad (4.32a)$$

Values calculated for different seat materials are listed in Table 4.10.

TABLE 4.10

VALUES OF γ FOR VARIOUS SEAT MATERIALS

Material	γ
Vinyl	0.27
Nylon	0.607
Latex	0.83*

*Assumes no combustion of sulfur used for cross-linking.

The combustion reaction for urethane foam seat materials, which depends on the degree of crosslinking and the particular reactants used to produce the foam, is too uncertain to permit γ values to be calculated for this material.

Inclusion of γ in Equation 4.32a represents an approximation to the actual situation because it assumes that only the seat cover, or seat material, is burning while actually both the seat cover and seat padding can be involved. Therefore, the values of γ are in error to the extent that the seat padding or urethane foam--for which the value of γ could not be ascertained--is consumed in the fire. The calculation of γ also assumes complete combustion which does not occur. Nevertheless, use of the factor γ in Equation 4.32a provides a rough, but useful, approximation for putting O_2 depletion data on a common basis.

No attempt was made to calculate a similar factor for the CO production correlation (Equation 4.33) because the details of the reaction are too uncertain.

Data on the CO production and O_2 depletion from seat fires which were ignited <u>on</u> the seat are compared with the correlations suggested by Equations 4.31 and 4.32a in Figures 4.45 and 4.46. The lines shown on these figures are correlations of data obtained previously from gasoline fires in an automobile interior (4). Although there is considerable scatter in the data, Figure 4.45 shows that the CO data from seat fires cluster around the line representing data from the previous tests. This agreement adds to the utility of the correlation because it suggests that the correlation is independent of fuel for the conditions of these tests. Thus, the correlation might be expected to apply to burning gasoline, seat covers, seat materials, head liners, floor carpets, etc.

Data in Figure 4.45 also tend to indicate that CO concentrations from port 2 are greater than from port 3.

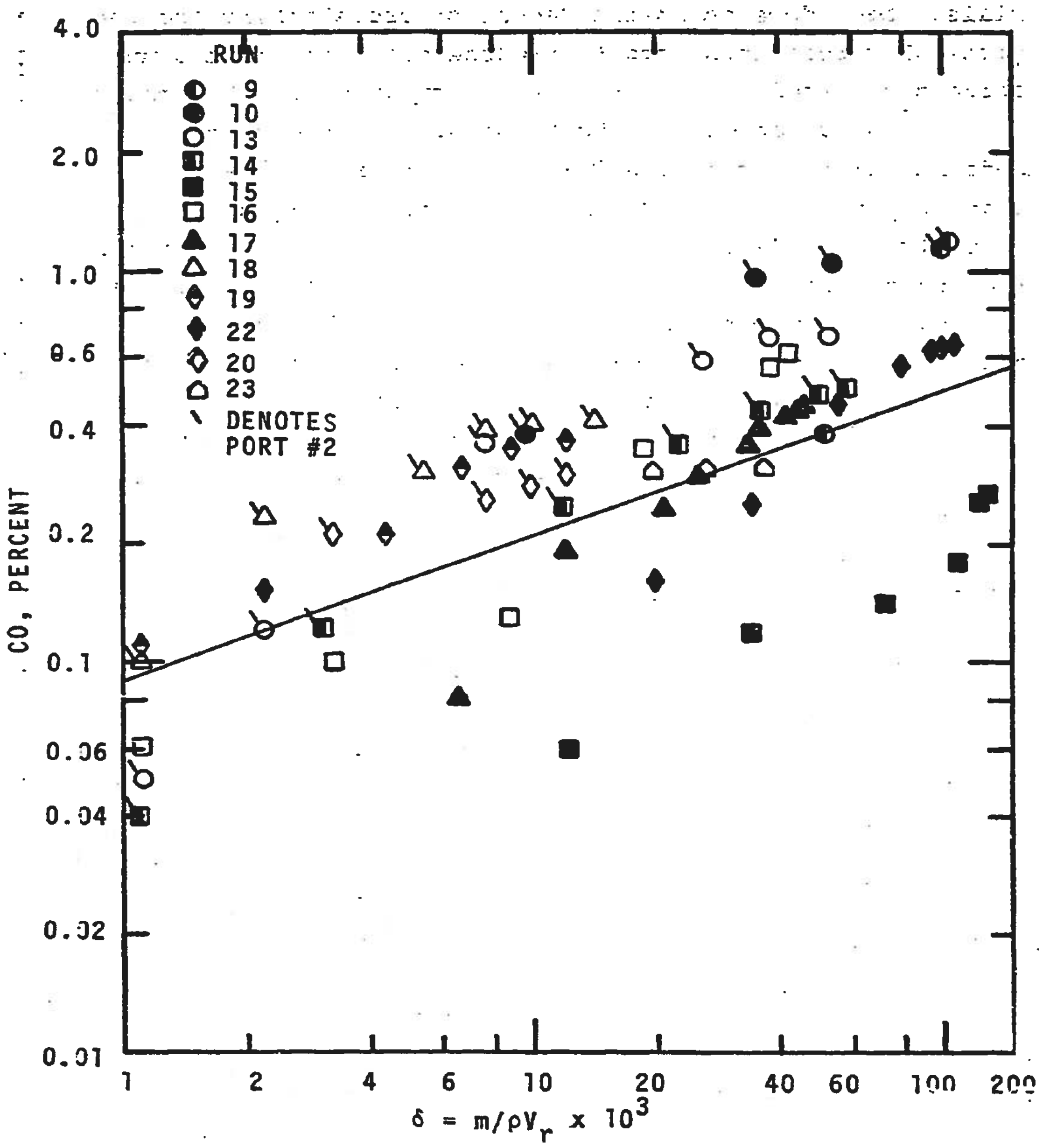


Figure 4.45. Carbon monoxide concentration as influenced by the dimensionless parameter $\delta = m/\rho V_r$ (only closed door cases).

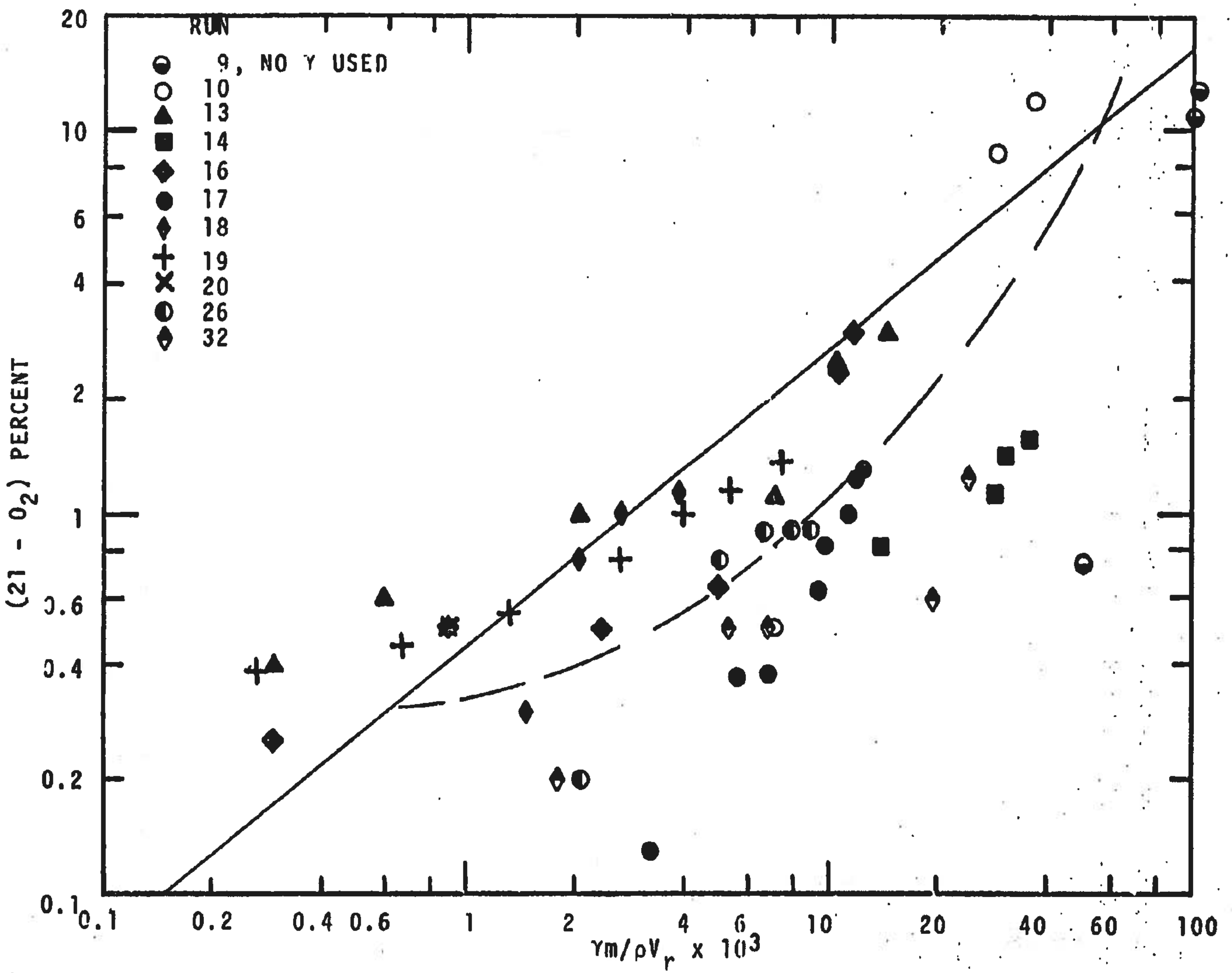


Figure 4.46. Oxygen concentration as influenced by the dimensionless parameter $\gamma m/\rho V_r$ for fires started on the front seat (both closed and open door cases).

However, the scatter of the data and the small difference in the data between the ports combine to make the apparent difference insignificant.

Information contained in Figure 4.45 should be useful for obtaining rough estimates of CO concentrations for fire situations in other automobile passenger compartments. The scatter of the data, which probably is an unavoidable result of the variable nature of the fires, precludes accurate predictions.

In Figure 4.46, the oxygen concentration data do not cluster around the correlation from the gasoline fires; rather they tend to fall below the correlation. There also appears to be a curvature (indicated by the dashed line in Figure 4.46) to the data. This curvature is more noticeable in Figure 4.47 which presents a correlation of oxygen depletion for tests in which the fire was started beneath (rather than on) the seat. Errors in Υ arising from incomplete combustion could explain why the data fall below the correlation for gasoline.

Data from Figure 4.46 should be applicable to situations in which the fire is in the front part of the car, except when the fire is mainly beneath the seat. If the fire is beneath the seat Figure 4.47 should give a better estimate. The scatter of data and the uncertainty caused by the apparent curvature in the plots allow only rough estimates of oxygen depletion.

4.3.2.4 Smoke density analysis: The decrease in light transmission caused by smoke from various seat fires provides a criterion for evaluating hazards attributable to the smoke.

The intensity of light transmitted through a given medium (a smoky automobile interior in this case) is given by:

$$\tau = \tau_o e^{-bL} \qquad (4.35)$$

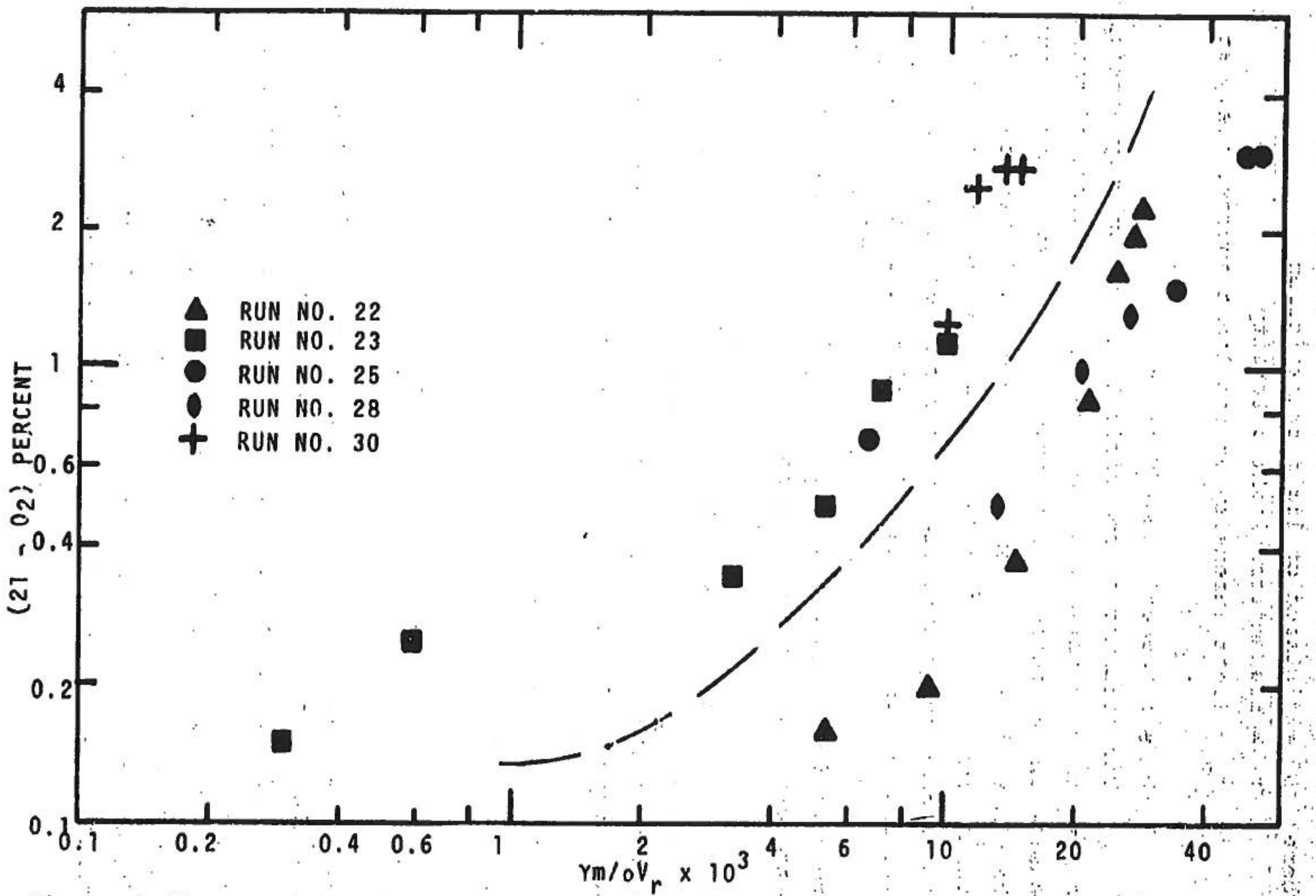


Figure 4.47. Oxygen concentration as influenced by the dimensionless parameter $\delta = Ym/\rho V_r$ for fires started under the front seat.

where L = distance of light transmission

τ = transmitted light intensity

τ_o = light intensity at the light source, i.e., at $L = 0$

b = attenuation coefficient

The attenuation coefficient is particularly significant to this investigation because it is a measure of smoke density in the automobile interior. (High values of b mean that there is a lot of smoke in the car and that vision is greatly impaired.) Therefore, data obtained from the photocell-light-source apparatus in the car were analyzed to determine changes in the attenuation coefficient with time.

If two light sources have the same value of τ_o and are at different distances L_1 and L_2 from their respective detectors, Equation 4.35 becomes:

$$\tau_1/\tau_2 = e^{-b(L_1 - L_2)} \qquad (4.35a)$$

by taking the ratio of the transmissions (Equation 4.35) for each source. Converting to natural logarithms gives:

$$\ln \frac{\tau_1}{\tau_2} = -b(L_1 - L_2) \qquad (4.35b)$$

or

$$b(t) = \frac{\ln [\tau_1(t)/\tau_2(t)]}{(L_2 - L_1)} \qquad (4.35c)$$

The notation, (t), is included in Equation 4.35c to emphasize that these quantities depend on time.

Calculations of attenuation coefficients were based on Equation 4.35c. $\tau_1(t)$ and $\tau_2(t)$ were obtained from the output voltages associated with photocells; L_1 and L_2 were 7.5 and 13.5 inches respectively. The complete results of b(t) are given in Table 4 of Appendix D. Attempts to obtain correlations of b as functions of burning rate or amount of material burned, which would be useful for predicting smoke density in other vehicles, were unsuccessful.

Figure 4.48 shows the dependence of light attenuation (smoke density) on time for two representative tests. In one instance the fire was started on the seat, and in the other, ignition was induced underneath the seat. (The logarithmic scale used in Figure 4.48 is only to allow a wide range of attenuation coefficients to be shown on the same graph; it has no physical significance.)

The general behavior shown in Figure 4.48 is typical of all tests. Smoke density rises to a maximum and then decreases as, presumably, fresh air leaks into the car. The maximum attenuation coefficient for under-seat fires always occurs after a much shorter time than the maximum for on-seat fires. The maximum attenuation coefficients and the time of burning at which the maxima occurred are listed in Table 4.11. Complete smoke density data are contained in Table 4, Appendix D.

An important criterion for assessing the smoke hazard of different fire situations is the time required for the smoke density (indicated by the attenuation coefficient) to reach a given critical level. This critical level is purely arbitrary. For example, it could be taken as the density at which an exit sign is obscured in a bus, the density which impedes a particular useful action or some other measure related to occupant safety. For this discussion calculation of an attenuation coefficient corresponding to a critical smoke density was based on two assumptions:

1. The critical smoke density would be obtained when τ/τ_o = 0.16. This assumption has been used by Gross, et al. (21) for comparison of the smoke hazards of many woods, polymers and fabric; specifically, it means that only 16 percent of the light is transmitted over the viewing distance.

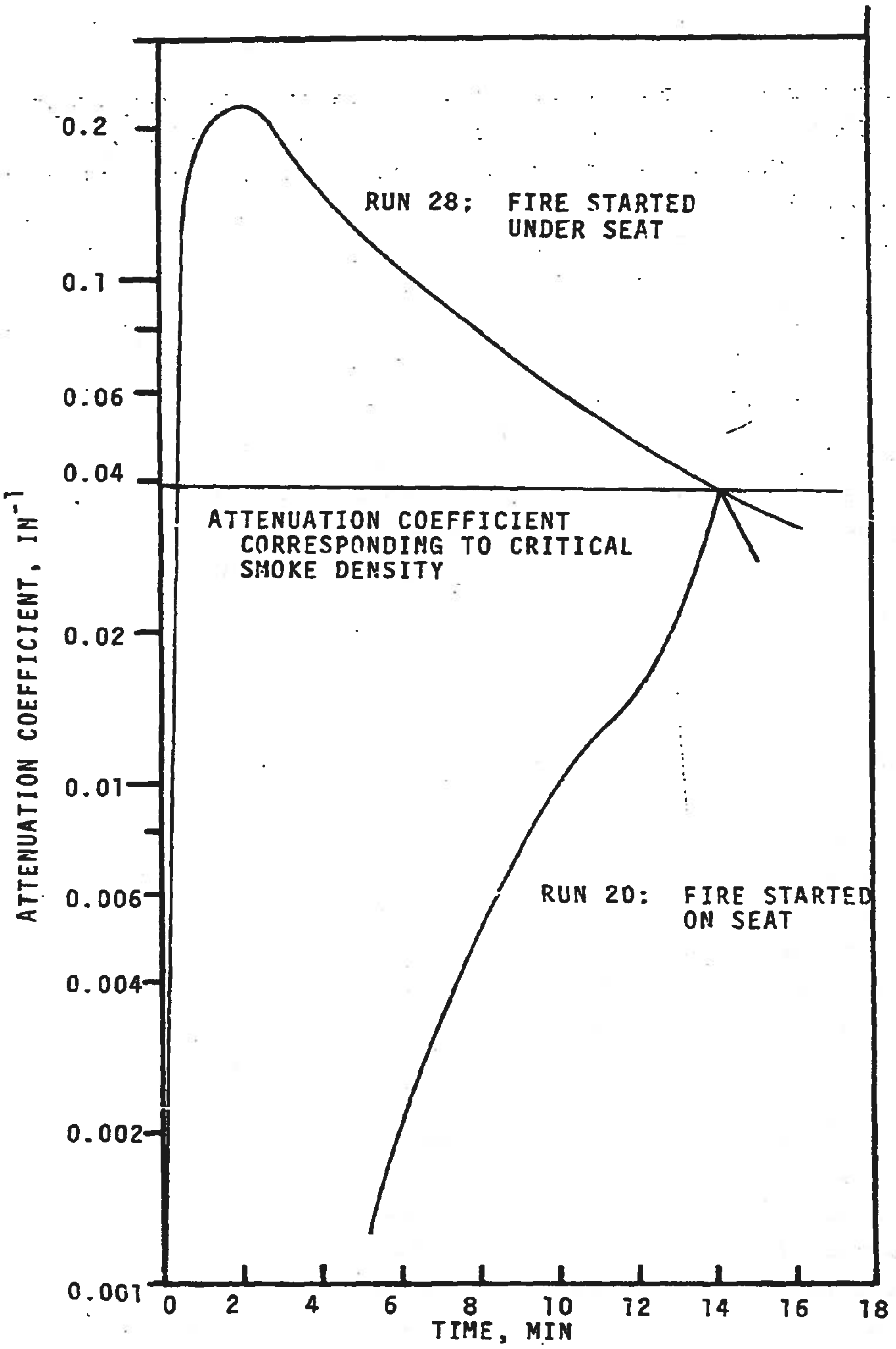


Figure 4.48. Typical variations of attenuation coefficients with time.

2. The viewing distance is 4 ft. Use of these assumptions in Equation 4.35c gave a critical attenuation coefficient of 0.038 in^{-1}. This value is also shown on Figure 4.48.

Times to reach a given critical smoke density for the various seats burned in these runs are listed in Table 4.11. Although the definition of the critical smoke density is quite arbitrary, the information is very useful for comparison because all fire situations are put on a common smoke density basis.

The results on time-to-reach-critical-smoke-density presented in Table 4.11 are mainly useful for comparisons of the hazards of the various seat fires. For instance, it is quite obvious that the smoke hazard associated with run #25 is much greater than with run #13. Likewise, as shown in Figure 4.48 and in Table 4.11, fires that ignite the bottoms of seats (foam padding burning) are much more dangerous (from a standpoint of decreased visibility) than fires on seats (fabric burning). With the exception of run #22 the times required to reach the critical smoke density are much less for below-seat ignition than for on-seat ignition. Thus, an occupant's ability to function will be impaired by smoke much sooner if the seat is burning from underneath.

Information presented in Table 4.11 also suggests that nylon covered seats present less of a smoke hazard than vinyl seats. Fires started on seats show that the time to reach critical smoke density is considerably longer for nylon-covered seats than for vinyl seats. The critical smoke density, 0.038 in^{-1}, was only barely exceeded during tests on any nylon covered seats; in fact for run #19 with nylon the critical smoke density was never reached. Therefore, physical and psychological hazards accompanying decreased vision, as well as possible hazards caused by smoke particles, can be expected to be noticeably less for nylon seats than for vinyl covered seats.

TABLE 4.11

CRITICAL PARAMETERS RELATING TO SMOKE IN AUTOMOBILE INTERIORS

Test	Seat	b_{max} (min)	Time of b_{max} (min)	Time to Reach Critical Smoke Density (min)	Seat Mat'l	Cumulative Weight Loss at Time of Critical Smoke Density
7	'70 Impala	0.04	14	13	V	270
8	'70 Mustang	0.14	6	2.1	V	65
9	Urethane Foam Mockup	Apparatus failed				
10	Latex Foam Mockup	0.04	0.75			150
11	Test aborted					
12	'69 Charger	0.08	3	1.6	V	25
13	'68 Rambler	0.24	13	7.4	V	275
14	'68 Plymouth	0.04	14	14	N	395
15	GM	0.56	10	1.5	V	110
16	'69 Ford	0.26	15	2.3	V	100
17	'69 Impala	0.07	11	1.5	V	45
18	GM	0.044	10	9.2	V	205
19	'67 Dodge	0.01	11	-	N	-
20	?	0.04	14	14	N	190
21*	Test aborted					
22*	'70 Superbee	0.13	5.5	4.9	V	550
23*	?	0.30	4	1.1	V	25
24*	Data not taken					
25*	?	0.22	4	0.7	N+V	200
26	'67 Torino	0.11	3	1.6	V	25
27	Test aborted					
28*	'69 Pontiac	0.22	2	0.2	N	50
29	'69 Chevelle	0.06	5.5	4.2	V	70
30*	'69 Chevelle	0.26	6	0.3	V	180
31	Apparatus burned up					

*Ignition from beneath seat.

Although differences in smoke density for various seat fabrics are quite pronounced, the differences between foam padding and seat fabrics are even greater as noted above.

4.3.2.5 Temperature measurement: During all tests temperatures were measured at six locations inside the car and at three locations on the outside of the body of the passenger compartment (refer to Figure 4.41).

Figure 4.49 indicates the temperature variation with time in a closed-door run for which the fire was started by igniting 6 cc of gasoline on the front seat. The behavior is typical of small fires started on front seats in enclosed passenger compartments. The lowest temperature occurs at the thermocouple nearest the floor, behind the front seat (thermocouple 5). Highest temperatures always occur near the ceiling, as expected, but temperatures near the ceiling in the back of the car (thermocouples 3 and 4) are usually higher than those in the front even though the fire is on the front seat. The outside metal roof temperature at the back of the passenger compartment (thermocouple 9) is also higher than the roof-body temperature at the front (thermocouple 8). These higher temperatures at rear sections of the passenger compartment are somewhat surprising because the fire is in the front of the compartment. However, this result does agree with previous results from fires in automobiles (4).

The behavior is different for large fires, such as occur when a door or window is open during burning. Temperatures under these conditions are shown in Figure 4.50. The passenger's side-front door was open for the first five minutes of the test and the fire was started on the front seat. Much higher temperatures occur when there is a fresh air supply, as a comparison of Figures 4.49 and 4.50 indicates. Also, contrary to the case when the passenger compartment is completely closed, the highest temperatures in the open-door

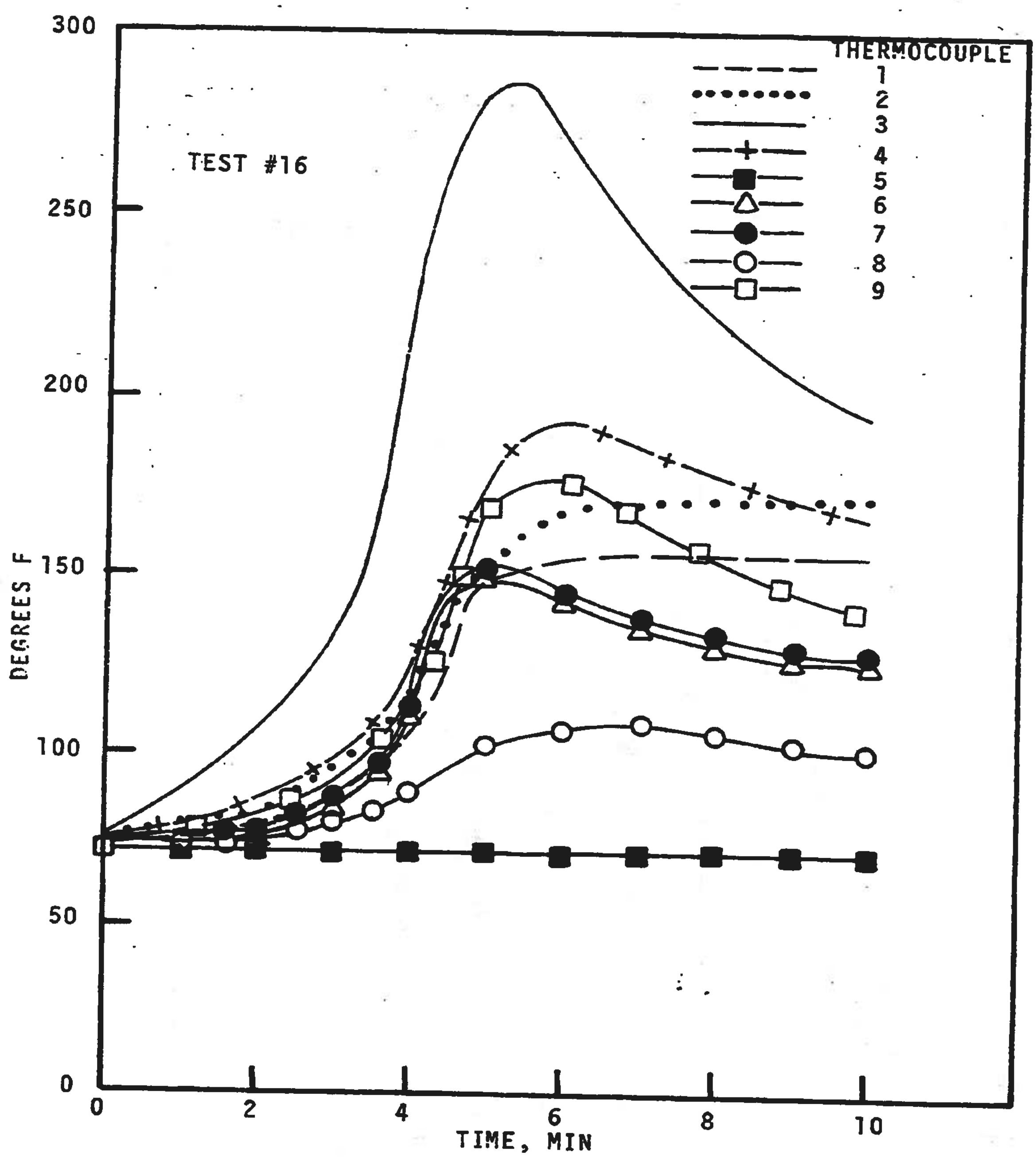


Figure 4.49. Temperature variation with time at various locations when ignition was on the front seat and the passenger compartment was entirely closed.

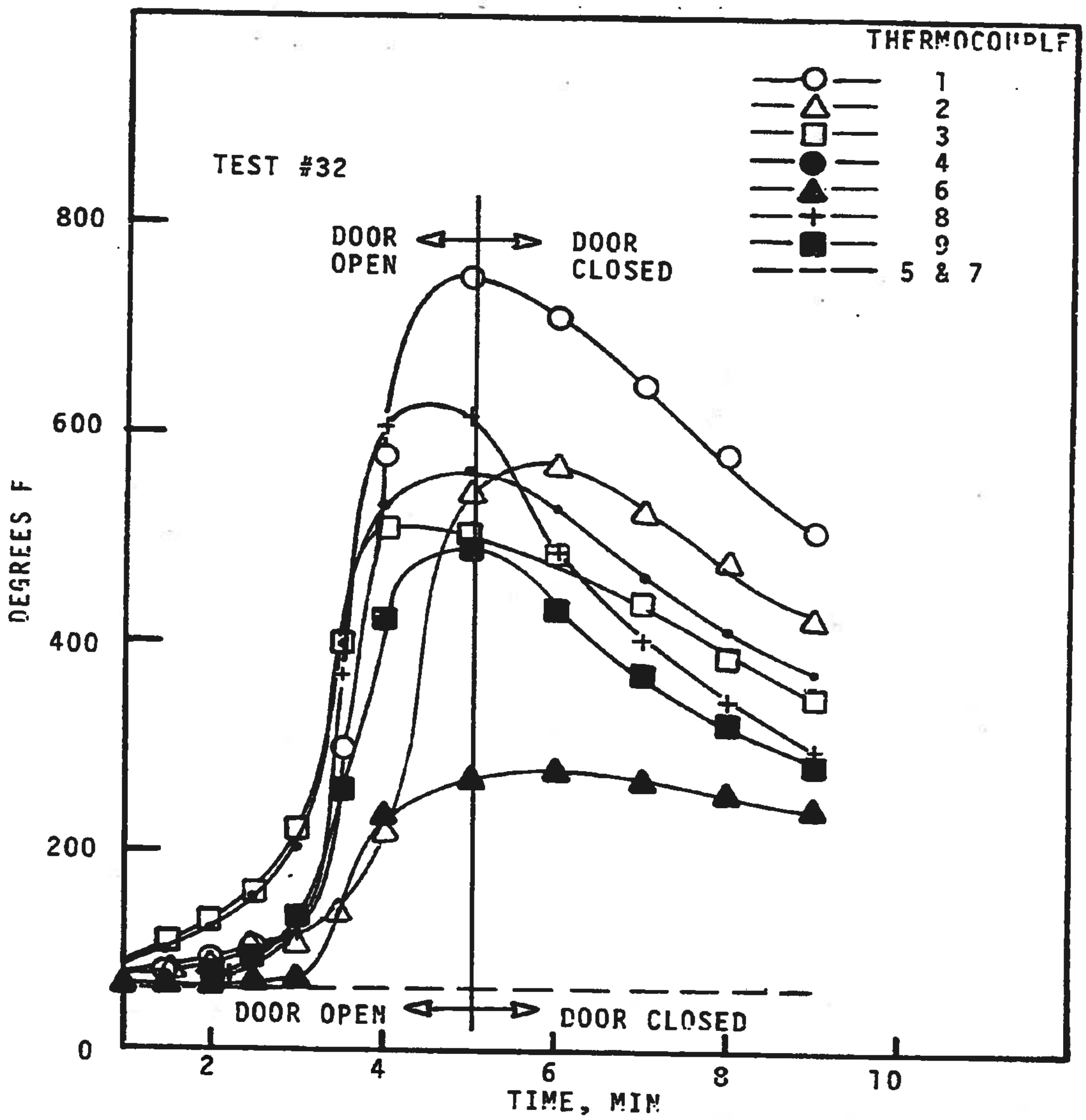


Figure 4.50. Temperature variation with time at various locations when ignition was on the front seat and one door open.

case occur in the front of the passenger compartment (thermocouples 1 and 2, and 8 which is on the outside at the front of the roof).

Several attempts were made by dimensional analyses to obtain a temperature correlation that is more generally applicable than a series of temperature-time curves for individual tests. The most successful correlation is illustrated in Figures 4.51 and 4.52. Figure 4.51 shows data for thermocouple 3, where the highest temperatures usually occurred: Figure 4.52 shows data for thermocouple 9 which indicates the hottest temperatures of the metal on the outside of the automobile body. The data suggest a relation of the form

$$T = CH^{\xi} \qquad (4.36)$$

where ξ = constant

C = a constant that depends on position in the car

H = the theoretical amount of heat released from the fire and is equal to the mass of fuel burned times the heat of combustion

The data shown in Figures 4.51 and 4.52 only apply to the period of increasing temperature in the interior. A correlation could not be obtained for the period during which the burning rate decreased and heat losses became significant. No significant improvement in the correlation was obtained by attempts to include other variables such as burning <u>rates</u>. The reason is probably due to the fact that the heat released during combustion is the overwhelming factor in heating the air and the automobile body.

Data from a test (#32) in which a door remained open and a large fire resulted are included in Figures 4.51 and 4.52. Since test #32 conforms as well as any of the other runs to the general trend line, it appears that the form $T = CH^{\xi}$ <u>might be</u> generally applicable regardless of fire

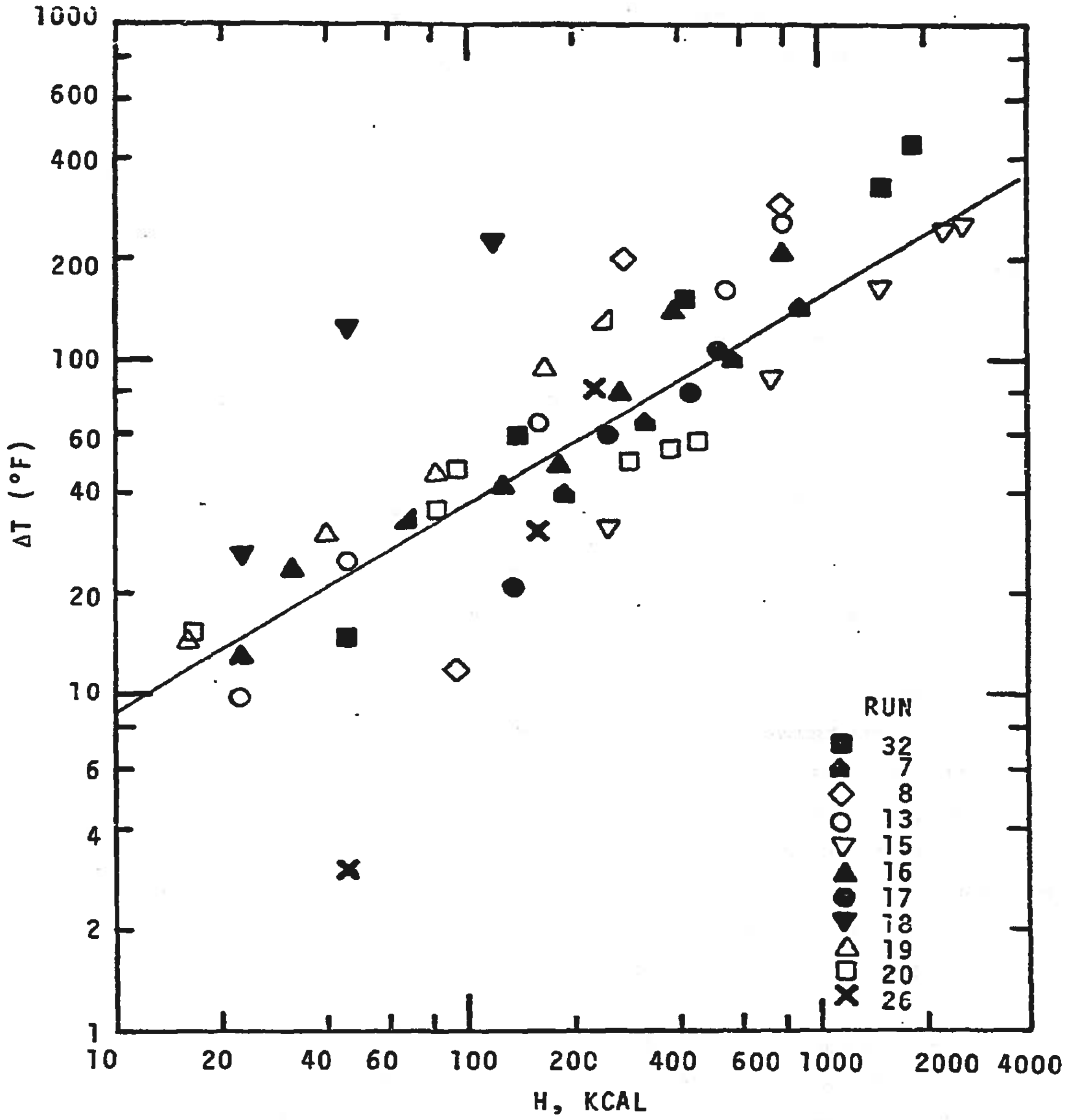


Figure 4.51. Temperature rise at thermocouple 3 (inside, rear ceiling) as influenced by heat released (ignition on seat, both open and closed door runs).

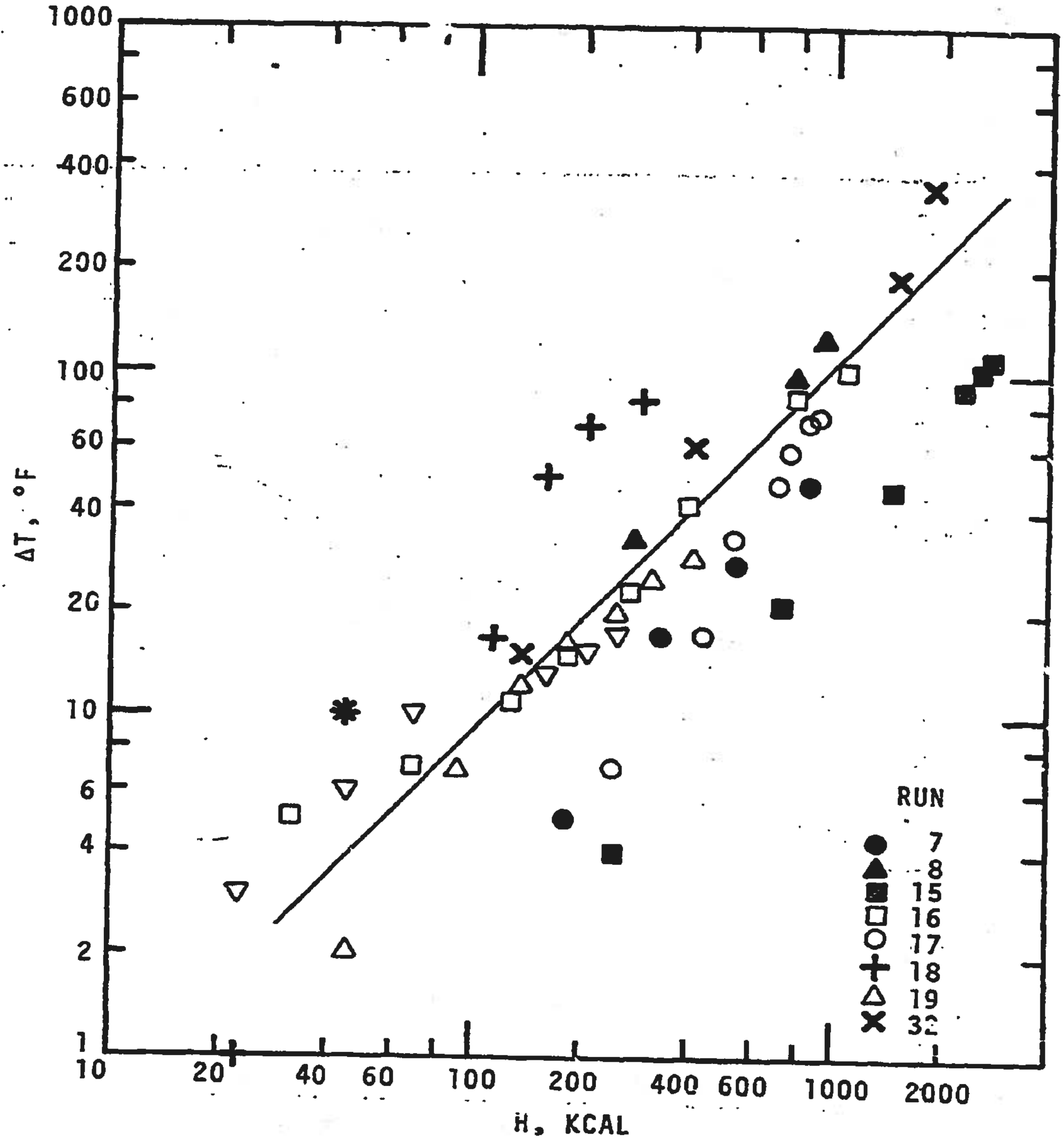


Figure 4.52. Temperature rise at thermocouple 9 (outside, rear roof) as influenced by heat released (ignition on seat, both open and closed door runs).

conditions. The scatter of the data precludes a more positive conclusion.

The scatter in the data of Figures 4.51 and 4.52, combined with the fact that the temperature change appears to be an elusive or obscure function of position (recall that the temperature in the rear of the interior for a completely enclosed fire--no doors or windows open--is higher in the rear than in the front even though the fire is in the front) precluded a correlation of temperature with position.

4.3.3 Summary of a "Real" Automobile Interior Fire

Although these vehicle interior fire tests constituted reasonable simulations of actual fires and generated useful information, much can still be learned from detailed investigations of "real-life" vehicle fires. During this contract period, 12 vehicle accidents involving fires, and in some cases fatalities, were investigated. Details are given in Appendix B. One fire, in particular, was examined quite exhaustively, including running ignition and burning tests on the interior materials. The details are presented in Appendix B starting on page B-213; only a brief summary will be given here.

At about 4:30 PM August 12, 1970, a woman drove her new, 1970, red Chevrolet Impala from her home to the parking lot of a Norman, Oklahoma, supermarket less than a mile away. Within about 5 minutes after her arrival the store manager announced that a red Chevrolet was on fire outside the store. He first called the fire department, and then he tried to extinguish the fire with a 2-1/2 gal soda-acid portable fire extinguisher without success. A construction worker had already failed in an attempt to extinguish the fire with an ABC powder extinguisher.

The fire department received the call at 4:39; they estimated arrival at the scene within 3 minutes with a Class A pumper They extinguished the fire with a water fog handline after disconnecting the battery. The fire crew estimated that less than 3 minutes elapsed between their arrival and the time the fire was out. Thus, about 11 minutes had elapsed between the time that the fire started and the extinguishment.

The interior of the car was severely damaged. The fire evidently spread from the instrument panel up to the sun visors, then backward across the headliner and the front seat to the rear. The fire spread was rapid as evidenced by the lack of severe damage to the roof exterior paint and the windows, two of which were partially open.

Samples were taken from the materials remaining in the car for burning rate (FMVSS 302-large cabinet version) and ignition tests. Subsequently, new materials of the same color and style were purchased from the manufacturer and subjected to the same tests. Table 4.12 summarizes the results of the burning rate tests, and Figure 4.53 shows the results of the ignition tests.

The burning rates in Table 4.12 and Figure 4.53 provide a basis for reconstructing the chain of events in the fire spread. The investigation showed that the fire started through an electrical malfunction in the instrument panel, burned through the acrylic window on the speedometer and up to the sun visor. The radiant heat from this fire preheated the front seat, although probably at irradiances too low to cause ignition. As the fire spread to the headliner, the increased radiant heating from the front part of the headliner increased the irradiance to the front seat. At this point the radiant heat transfer from the headliner to the top of the front seat back was on the order of 1 cal/cm^2-sec. According to Figure 4.52 the vinyl seat back would ignite in something like 5 sec. Once the front seat was burning, it reinforced the heating on the headliner, causing it to "flash." According to Subsection 4.3.2.2, the burning rate of the headliner

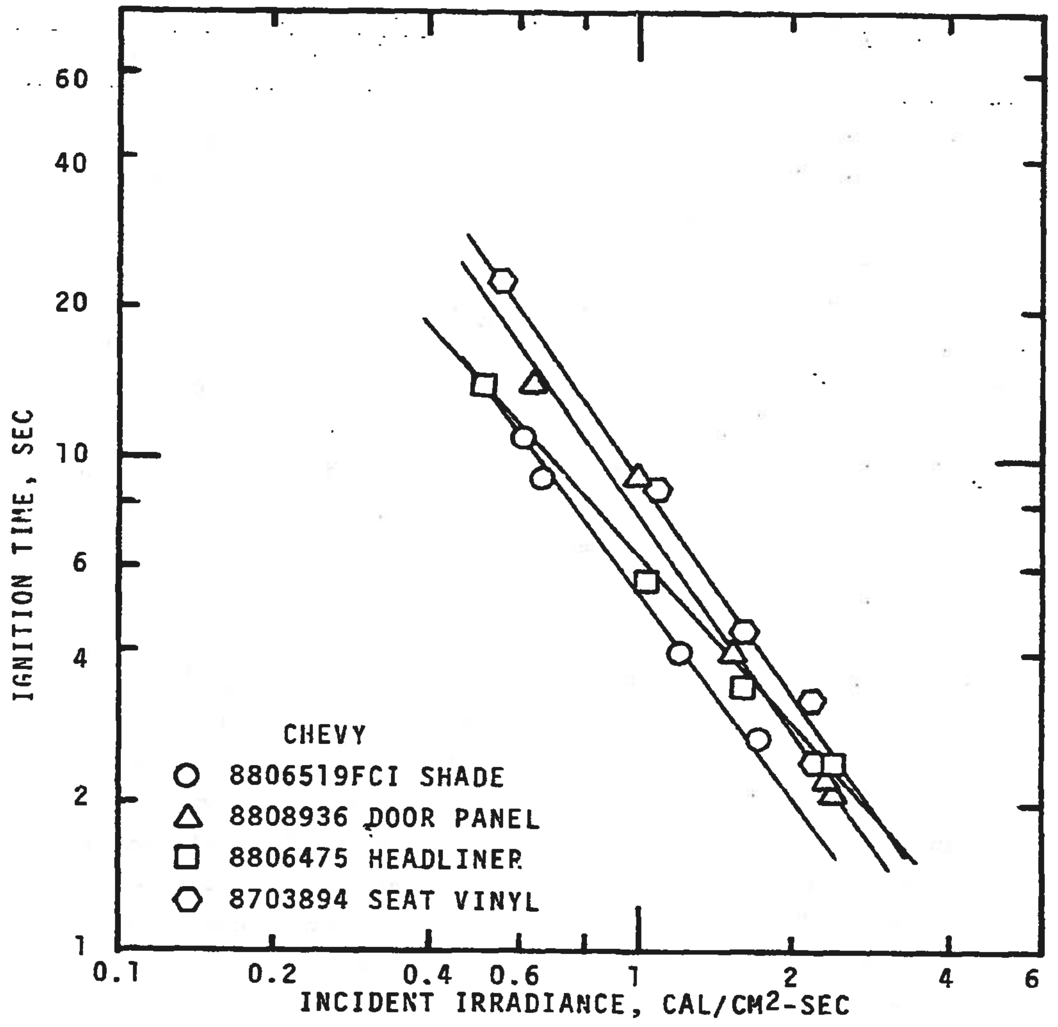


Figure 4.53. Ignition time of 1970 Chevrolet Impala interior materials.

TABLE 4.12

HORIZONTAL BURN RATES OF IMPALA MATERIALS

Item	Average Burning Rate, in/min From Damaged Car	 New
1. Headliner	7.6	9.1
2. Seat vinyl	3.8	
3. Seat foam	4.4	
4. Rear seat facing	1.9	
5. Carpet	0.4	
6. Doorpanel composite		SE/NBR*
a. Vinyl covering	--	3.5
b. Matrix	--	6.0
c. Gray cardboard pad	--	0.8
d. Brown pressboard back	--	SE/NBR
7. Sun visor, composite		SE/NBR
a. Vinyl covering	--	8.0
b. Cotton padding	--	3.1
c. Matrix	--	1.7

*SE/NBR = Self-extinguishing, no burning rate.

could be on the order of 175 inches per minute; thus the headliner was probably consumed in a matter of 30 seconds. At these flux levels, the rear seat could ignite in a matter of 5 seconds. Thus, from the time that the headliner first ignited, the entire vehicle interior was probably engulfed in flames in less than one minute.

This postulate of rapid fire spread is also consistent with the results of the open-door interior fires in the laboratory (presented in the preceding subsection) for which a small fire started in the front seat ignited the headliner in about 3 to 4 min. Once the headliner started to burn, it virtually flashed, and the burning rate of the front seat increased sharply, indicating rapid spread of the seat fire to previously unburned portions.

The value of both the laboratory flammability test and the vehicle interior fire simulation has been demonstrated. The fire build-up in this "real life" situation required 4 to 5 minutes, which agrees with the open-door tests. During this slow build-up period--prior to ignition of the headliner--the fire could have been extinguished rather easily with proper use of a hand fire extinguisher as will be discussed in Section 4.6. However, once the headliner ignited, it is doubtful whether the fire could have been extinguished in time to prevent severe damage to even the rear seat. Obviously, if any occupants had been in the vehicle at the time the headliner ignited, severe burns, and more likely fatalities, would have occurred.

In some ways, this fire was not typical of the usual interior fire. According to fire department records (see Section 4.7), the usual interior fire occurs with at least one occupant present who takes immediate measures to extinguish the fire by one means or another. In these cases, rarely does the headliner become ignited. Nevertheless, this unattended fire in the Chevrolet Impala clearly demonstrates that vehicle interior materials can support a rapidly burning fire which produces severe damage in a relatively short time if the fire is not controlled and has sufficient ventilation. The relatively rapid spread of the fire where preheating of materials occurs is characteristic of any combustible material, even if it is self-extinguishing, because once the material is ignited, the effect of preheating is not only sufficient to maintain burning, but also to accelerate flame propagation.

4.3.4 Conclusions and Recommendations

Fourteen conclusions relating to survival in vehicle interior fires are evident from this investigation:

1. The vehicle interior fire tests constitute a reasonable simulation of actual vehicle fires.

2. The results of the laboratory flammability tests on ignition and burning rates constitute a basis for estimating the time required and the thermal damage encountered in vehicle interior fires.
3. A fire which starts in the interior of a vehicle with all doors and windows shut does not result in widespread damage. By the same token, it does not pose a serious threat to occupants unless they are unable to egress quickly. Of greatest concern is the gagging or respiratory distress which was experienced by laboratory personnel upon entering the passenger compartment shortly after a test.
4. A fire which starts in the interior of a vehicle with a door or window open can completely gut the interior within less than five minutes after the fire starts. During the first three minutes, these fires build up slowly and then "flash" suddenly; most of the destruction occurs in a matter of about 30 seconds.
5. The headliner appears to be the primary culprit in flash-overs.
6. The intensity and nature of the ventilated, vehicle fire in which flash-over occurs is such that occupants would have little chance of survival.
7. Individual concentrations of oxygen, CO and CO_2 were never observed to reach immediately lethal values <u>except</u> when latex and urethane foam mock-up seats were burned. Therefore, survival times for gasoline- or seat-cover-fueled fires will not be controlled by concentrations of these gases, <u>unless</u> additive or synergistic effects lower occupants' tolerances to these gases. This observation agrees with earlier results from tests on small hydrocarbon-fueled fires in enclosed spaces.
8. Burning of latex and urethane foam mock-up seats produced rapidly lethal concentrations of CO and oxygen.

9. No significant dependence of gas concentration on position was observed (i.e., CO and oxygen concentrations were nearly uniform throughout the interior) when the passenger compartment was completely enclosed. This observation agrees with previous results of the effects of small hydrocarbon-fuel fires in enclosed spaces. No reliable measurements on the gas concentration as a function of position could be taken because of the very short burning time.
10. Changes in temperature, CO and oxygen concentrations from test to test are primarily functions of the amount of fuel burned.
11. The time required to reach an arbitrary critical smoke density in the interior is significantly shorter (and the situation potentially more dangerous) for fires which start under a seat than for fires that start on the top of a seat. The difference is due to the amount of smoke produced by the padding as compared to the seat fabric.
12. Nylon covered seats appear to present less of a smoke hazard than vinyl covered seats.
13. The lethal concentration of CO and depletion of oxygen that resulted when foam mock-up seats were burned, combined with the rapid smoke accumulation when ignition was under the seats (foam was probably the primary fuel in these cases), suggests that foams used in automobile seats present potent hazards to occupants trapped in a burning interior.
14. The FMVSS 302 burning test (or similar tests) may be more relevant to the vehicle interior fire problem than has been generally believed.

Based on these conclusions, four future courses of action are recommended:

1. A consumer education program which familiarizes the public on the origin and nature of vehicle fires and on the

remedial steps to be taken to minimize personal injury and property damage in the event that a fire does start.

2. The constituents in vehicle materials which generate, upon burning, noxious (or lethal) gases and/or dense smoke need to be identified with a view toward minimizing their use in vehicle interiors. Current FAA studies on the toxicity of combustion products from fabrics could supply much of the required information.
3. The preliminary agreement among laboratory flammability tests, vehicle interior fire simulations and "real life" vehicle fires should be validated by additional analytical and experimental work and in-depth, on-site investigation.
4. The present studies have been restricted to vehicle fires which are started in and are confined to the interior. Of far more concern, particularly from the fatality standpoint, is the fire initiated externally by fuel spillage which ultimately involves the vehicle interior. Thus, the external fires should be investigated along the same avenues as the interior fires have in this study.

4.4 FUEL MODIFICATION

This section on fuel modification for motor vehicles is a continuation of work initiated under the previous contract, FH-11-7303. This effort was limited to a review of the more pertinent literature in order to assess the merit and technical feasibility of modifying vehicle fuels for reducing the incidence of post-crash fires (4). Thus, the present effort under this contract, FH-11-7512, amounted to an updating of the literature review.

In the previous report (4) it was concluded that emulsified and gelled jet fuels proposed for aircraft offered the greatest promise for controlling fire hazards by reducing: (1) the chances of fuel ignition; (2) the rate of fire growth and fire intensity if ignition occurs; and (3) the amount of fuel spilled from ruptured fuel tanks and fuel lines.

All of the published results on modified fuels have been directed towards aircraft applications. However, these techniques should also be applicable to automotive fuels because of their close chemical similarity to aircraft fuels. The major difference in application is that automotive fuels are currently burned in piston engines while modified aircraft fuels are largely proposed for use in turbine engines.

The previous report analyzed the advantages and disadvantages of two approaches:

1. The pre-gelled or pre-emulsified fuel approach wherein the gel or emulsion is pumped into the fuel tank at the service station, and the modified fuel is burned in the engine.
2. The rapid-gel approach wherein conventional fuels are burned in the engine in the pre-crash modes, but chemicals which rapidly gel the fuel are injected into the fuel tank upon crash impacts.

The previous report also mentioned that practical application of either of these approaches requires the fulfillment of several criteria, the most important of which are:

1. A reduction in the rate of fire build-up and the rate of fire spread must result. (No ignition is a total reduction in these rates.)
2. The approach must necessitate no more than minor modifications of present fuel systems (including commercial distribution systems) in order to insure widespread acceptance.
3. The chemicals, gels, or emulsions must be stable under the extremes of storage conditions.
4. The modified fuel must not damage the engine.
5. The chemical agents must not contribute to air pollution and should be of only moderate acute, local or systemic toxicity (i.e., should not be more toxic than the fuel component).

A sixth criterion might be added to this list:

6. To gain popular acceptance of the modified fuels the use of fuel modifiers should not raise the cost of the fuel significantly.

Since completion of our last report under Contract FH-11-7303, additional studies relating to modified fuels have been published. These new studies have not suggested any new approaches for implementing the use of modified fuels. In fact, only a few of these studies present new information that is applicable to modification of automobile fuels. Those studies which do suggest significant advances beyond information previously available are discussed in the remainder of this section.

4.4.1 Progress in Pre-Gelled or Pre-Emulsified Fuels

Table 4.13 presents our previous evaluation of the pre-gelled or pre-emulsified fuel approach except that it

TABLE 4.13

CHARACTERISTICS OF THE PRE-GELLED OR PRE-EMULSIFIED FUEL APPROACH

Advantage	Problem Areas
1. Protection is continuous and not dependent on the response of people or mechanical systems for gel or emulsion formation.	1. Gels and emulsions have a yield stress which makes it extremely difficult for them to be atomized in a conventional carburetor.
2. The hazard of fuel leakage and non-collision fire is reduced except at high-pressure transfer locations.	2. Promising emulsions and gels may not be compatible with standard construction materials and might contribute to air pollution
	3. Instability in storage may be a problem, especially with emulsions.
	4. Gels and emulsions tend to clog fuel filters and may not flow under the influence of gravity, thus necessitating redesign of fuel-feed devices.
	5. Gels and emulsions used must not break down on transfer from one storage tank to another.
	6. The necessity of including a gelling or emulsifying agent in all fuel used could increase the price of fuel substantially.

adds a new problem area, Item 6, which relates to cost. A recent study (22) estimated that use of a gelling agent "at a 2 percent concentration was expected to add approximately 25 percent to the cost of jet fuel." In view of the U.S. shortage in petroleum, which will surely drive gasoline prices upwards, it is unlikely that the average motorist will accept an additional increment.

Separate formulations by Dow Chemical Company (23) and by Anheuser-Busch, Inc. (24) indicate that progress has been made towards overcoming the difficulties associated with fuel flow (Problem Area 4 in Table 4.13). Because of the low yield stresses and low viscosities of these formulations, it is also possible that either the Dow or Anheuser-Busch formulation would atomize in a standard carburetor, thereby overcoming the difficulty mentioned in Problem Area 1. No tests of atomization in carburetors have been reported.

The Dow report (23) discusses development of a gelled fuel that provides protection against fires and explosions while maintaining the relatively low viscosity required by conventional aircraft fuel systems. For instance, the flow rate of this fuel through an oval orifice (the shape of which is shown in Figure 4.54) under gravity conditions was equal to the flow rate of an unmodified fuel.

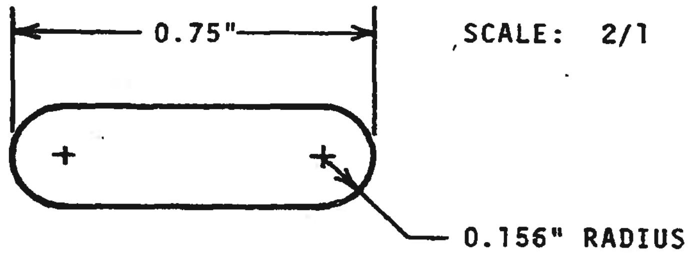


Figure 4.54. Shape of oval orifice used in gravity flow tests of Dow Chemical's free-flowing gel.

Flow rates through inclined pipes were less than those for the unmodified fuel, but they were significantly greater than flow rates of other thickened fuels. Figures 4.55 and 4.56 (Reference 23) compare the gravity flow of the Dow formulation and Jet A in a 3/16-in ID pipe. There is quite a difference between the flow rates at low pressure heads, but the flow rates rapidly approach each other with increasing heads. It is entirely possible that the flow rates of these two fuels through this pipe would be equal at the operating pressures of conventional automobile fuel pumps.

The explosion resistance of the Dow formulation was confirmed by Air Gun Explosion Tests performed by the Federal Aviation Administration's National Aviation Facilities Experimental Center (NAFEC). The Dow formulation received ratings of "2" in the Air Gun Explosion Tests. This rating indicates 70 to 98 percent reduction of fire hazard, no explosion and slight flaming. Thus, the Dow formulation offers significant promise for reducing fire hazards in vehicle crashes.

In the Air Gun tests a polyurethane cartridge containing one gallon of fuel in a polyethylene bag is propelled at 90 MPH into a steel mesh screen. On impact with the screen the fuel is sprayed across five fire pots. Visual observation of the resulting fire is used to ascertain the relative safety of the fuel.

The final composition of an acceptable Dow fuel formulation is given as:

Jet A-1	344 pounds
Experimental resin XD-7038.00	6 pounds
DOWANOL DE	0.23 pounds
28 percent Ammonium Hydroxide	0.005 pounds

The report by Anheuser-Busch (24) also discusses development of a "free-flowing gelled fuel" that is effective in reducing the fire hazard of a jet fuel, yet "could be adapted readily to existing fuel systems." The most satisfactory

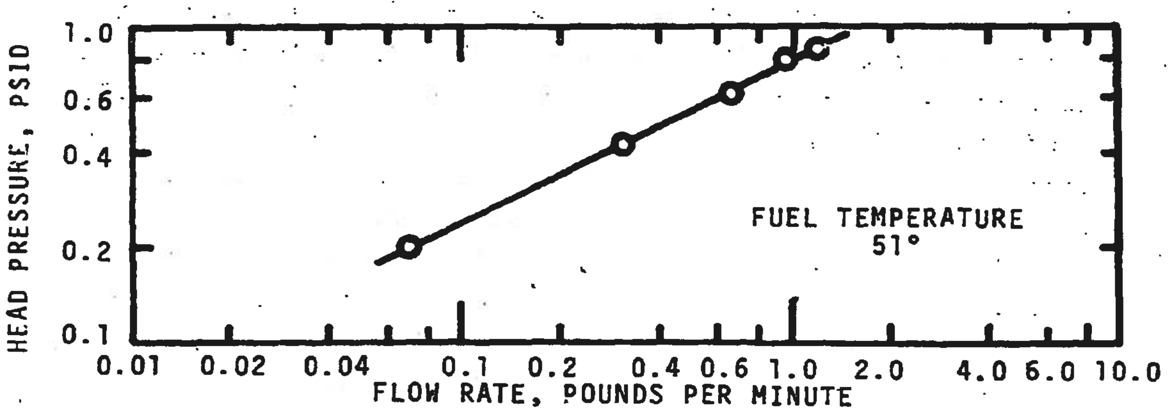


Figure 4.55. Flow of conventional Jet A fuel through an inclined pipe (3° slope) having an inner diameter of 3/16-inch and a length of 5 inches.

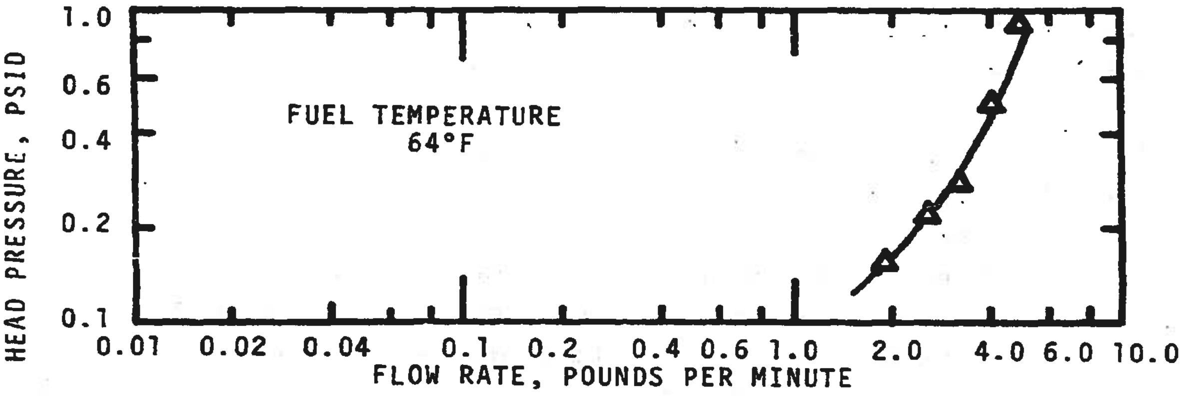


Figure 4.56. Flow of Dow, pre-gelled fuel through an inclined pipe (3° slope) having an inner diameter of 3/16-inch and a length of 5 inches.

gelled fuel formulated by Anheuser-Busch contained 2.52 percent of a proprietary, polyglucan derivative gelling agent in Jet A.

On the other hand the desirable free-flowing characteristics of the Dow or Anheuser-Busch formulations implies that they would leak more readily from ruptured fuel lines and tanks than the usual pre-emulsified fuels. The net safety benefit, then, is a trade-off between free-flow and a good rating on the Air Gun Explosion Tests.

Although the development of these free-flowing fuels is a boon to the pre-gelled fuel approach, to date only a preliminary evaluation has been reported, and the following questions remain to be answered:

1. Will the formulations atomize in standard carburetors?
2. Will the cost of these formulations be prohibitive?
3. Are the formulations stable under the extremes of storage conditions?
4. Are the formulations compatible with standard construction materials?
5. Will burning the formulations in automobile engines aggravate pollution problems or cause undesirable deposits in the engine?
6. Will the formulations reduce the incidence of fires, given the low yield stress and free-flow characteristics?

One recent study (25) suggests that the resistance of high yield stress safety fuels to atomization could be circumvented by incorporating a device in the fuel system that would break down the emulsion or gel just prior to carburetion. Suggestions for such an apparatus include "an ammonia dispensing system, a heat exchanger, a high energy mechanical agitator, or a system combining these approaches." Presumably, such equipment would permit use of any pre-emulsified fuels in a conventional fuel system with few other modifications, in which case the advantages of a free-flowing fuel become relatively minor with respect to carburetion. Of course, storage, compatibility with construction materials, transfer, cost and pollution problems would still have to be evaluated.

4.4.2 Progress in the Rapid-Gel Approach

Our previous report discussed in some detail why the rapid-gel approach seemed technologically feasible at present (4). Table 4.14 recapitulates the advantages and problem areas associated with the rapid-gel approach. No progress has been reported on injecting the gelling agent into the fuel, the effects of multiple injection points, and gelling rates of various agents. Until this basic information is developed, equipment for implementing the rapid gel approach cannot be designed.

4.4.3 Conclusions and Recommendations

Based on this updated literature review, the following conclusions are drawn:

1. Development by Dow Chemical of a free-flowing gelled fuel with demonstrated reduction in fire hazards and development of another free-flowing gelled fuel by Anheuser-Busch are significant steps towards making the pre-gelled fuel approach technically feasible for use in conventional fuel systems. The free-flowing characteristic of these gels does sacrifice a safety feature in that these gels could leak readily from ruptured fuel tanks and lines.
2. With respect to the pre-gelled or pre-emulsified fuel approach, problems such as atomization of the gelled fuel in a carburetor, pollution caused by burning the gelled fuel, increased fuel costs and storage stability remain to be evaluated.
3. The rapid-gel approach still seems technologically feasible at present. In fact, the advantages of the rapid-gel approach suggest it to be more suitable than the

TABLE 4.14

CHARACTERISTICS OF THE RAPID-GEL APPROACH

Advantages	Problem Areas
1. Existing fuel system can be used with only minor additions.	1. Protection is dependent on the triggering mechanism, which must be fast, reliable and not sensitive to minor accelerations.
2. Existing storage, transportation and distribution techniques for fuels need not be changed.	2. Design of a system to inject the gel-producing chemicals into the fuel system may be difficult because of the incompatible requirements of complete mixing and fast reaction to attain safety features.
3. The gelling agent is not consumed with the fuel, and therefore the pollution problem is avoided, toxicity problems of handling are reduced, and the necessity for quantity production of the agent is greatly reduced.	3. Because the fuel system is not designed to operate with gels, the vehicle becomes inoperable once the gel-formation mechanism is triggered.
	4. This approach does not modify residual fuel in any of the system except the fuel tank.

pre-emulsified fuel approach for use with automobiles because the normal fuel is still burned in the engine. For this reason the rapid-gel approach does not raise questions on pollution, increased fuel cost, and modification of fuel systems and fuel storage facilities which are required in the pre-emulsified fuel approach.

4. The techniques for introducing the gelling chemicals in the rapid-gel approach have not been advanced over the past few years.

If modified fuels for motor vehicles are assumed to provide worthwhile safety features, then the following recommendations apply:

1. Since the rapid-gel approach has many advantages over the pre-emulsified fuel approach for use in automobiles, then important questions relating to optimum gelling agents and design and location of injection ports need to be resolved. Answers to these questions will require considerable time and effort.
2. The uncertainties that still exist as to whether pre-emulsified fuels will function in conventional automobile engines and whether they will be effective in reducing fire hazards significantly, can be resolved by:
    a. Testing pre-gelled fuels (such as the Dow and Anheuser-Busch formulations, which appear to have the best opportunity for success) in automobile engines.
    b. Performing crash tests on automobiles to compare the effectiveness of the pre-emulsified and rapid-gel approaches.

4.5 DOCUMENTATION OF FUEL SYSTEMS CONSTRUCTION PRACTICE

A minor subtask under the general task related to improving the safety of automotive fuels involved an attempt to analyze the relative merits of improving the integrity of fuel systems as compared to the feasibility of using a crash-insensitive fuel (fuel gels or emulsion as discussed in Section 4.4). This effort was to be developed from literature surveys on crash-insensitive fuel developments and on post-crash fuel spillage events. The entire subtask was therefore based upon the premise that the body of literature on these two subjects already surveyed under Contract FH-11-7303 and by other contractors for NHTSA (and NHSB) would be substantially increased during the two-year course of the present contract, FH-11-7512. Contrary to expectations, however, new developments and progress in the development of crash-insensitive fuels and literature related to those developments and progress have not been forthcoming, as discussed in Section 4.4 above. Similarly, the expected increase in interest in fuel containment and in fuel spillage was not evident in the available literature. The data required for any reasonable assessment of the relative merits of the two approaches to controlling spillage have simply not materialized. Therefore, in accordance with the instruction from the contract technical manager, this subtask was redirected to a preliminary assessment of the feasibility of obtaining data related to fuel systems integrity from: (1) an examination of crashed vehicles in salvage yards, and (2) the standard police accident reports and fire department run reports that were being accumulated for other purposes under this contract (Sections 2.2 and 4.7). The remainder of this subtask was to be directed towards comparative documentation of construction practices for the 1972 models of a representative number of vehicles that had been analyzed by Fairchild-Hiller under Contract FH-11-6919 in 1968 and 1969 (26).

4.5.1 Feasibility of Obtaining Fuel Systems Integrity Data from Salvage Yard Surveys

Salvage yard surveys appeared at first to be the most accessible possible source of data for several of the tasks under this contract, including the fuel system integrity subtask. Observation of about two hundred crashed passenger cars was completed at four major automobile salvage yards in the Oklahoma City area. During the conduct of this survey, several basic problems became apparent which tended to make salvage yard data less useful than had been expected and which tended to make salvage yard surveys neither feasible nor productive without excessive cost.

A major problem in conducting salvage yard surveys is in determining the damage that occurred in the original crash, first in attempting to see the damage and second in distinguishing between crash and post-crash damage. In order simply to see the damage in many cases, heavy equipment would have been required to raise and position the vehicle and a considerable amount of disassembly would have been necessary. Very often, the wheels had been removed from the vehicle so that it was sitting on the brake drums directly on the ground. To bring in heavy equipment and to dismantle the vehicle partially would have involved a certain amount of disruption of the yard's operations as well as costs greatly in excess of those budgeted for this task. Because of the costs, this more perspicacious approach was abandoned, and methods of general observations of the vehicle were attempted.

In attempting to determine percentage frequency of types of accidents and types of vehicles represented by the salvage yard vehicle population, general observations were made on about two hundred vehicles. Despite early indications that this approach would be unproductive, it was continued until it was undeniably clear that the effort was essentially futile for all the intended purposes. Very early in the survey, it was apparent that scavenging of parts, either basic components or sections of sheet metal, by the salvage yard owners seriously interfered with data collection. As the survey progressed, it became evident that considerable damage was inflicted on the vehicles during normal yard operations, this damage being either sheet metal crush from moving the vehicles or disassembly damage such as crushed, cut, or torn fuel lines, retaining straps and clips, bolts, and even parts such as bowls on fuel pumps. Attempts to separate the secondary post-crash damage from the original damage by studying salvage yard records (sometimes including photographs of the vehicle taken shortly after the crash) and through intensive questioning of salvage yard employees were so unproductive that the survey was abandoned.

Two additional problems were observed in conducting the survey. At the beginning, it was assumed that the mix of vehicles and accident types represented by the salvage yard population would be for all practical purposes a random sample from the road and therefore similar to the accidents and accident-involved vehicles on the road. This premise proved in error. Each of the salvage yards visited and a number of others contacted by telephone had operating policies of selective acquisition which precluded construction of a random sample even from the combined populations of several salvage yards. Basically, these selective acquisition criteria were related to type of damage, age of vehicle, and manufacturer of vehicle. Salvage yards tended to specialize in newer vehicles or older vehicles or vehicles from one or two manufacturers. Some limited their acquisitions to vehicles impacted from certain directions, so that if a body shop needed front-end sheet metal and grilles, it contacted the salvage yard that buys side and rear-end collision-damaged vehicles. Consequently, the problems of statistical analysis associated with data from such sources were considered insurmountable at a small-effort level, supporting the decision to abandon the survey.

A final problem associated with salvage yard surveys is the identification of type of collision and severity of collision in order to associate these factors with the resultant damage. The only source for such information was police accident reports. For most of the vehicles in the salvage yards surveyed, information needed to retrieve the accident report was not available, particularly if the vehicle had been purchased in another state. This problem virtually eliminated making a useful salvage yard survey.

4.5.2 Feasibility of Obtaining Fuel Systems Integrity Data from Standard Police Accident Reports, Multidisciplinary Accident Investigation Reports, and Fire Department Run Reports

During the normal course of activities in the present research program, police accident investigation reports from several states were reviewed for escape-worthiness data (Section 2.2 of this report). These reports contain no useful information on fuel systems integrity. At most, fuel spillage or fire is briefly mentioned in the narrative. No discussion of failed components appeared in any single report.

The Multidisciplinary Accident Investigation Team reports are currently the source of the most detailed reports on collision-induced fuel system damage. Approximately 150 of the MDAI Team reports were obtained and examined for adequacy of detail on fuel system damage. Nineteen of the case reports involved actual fuel leakage. Twelve instances of tank rupture, four instances of filler neck failure, five instances of fuel line leaks, and one engine component leak were reported. Most of these failures occurred in relatively severe collisions.

Several thousand fire department run reports from four cities were surveyed. These reports covered runs to motor vehicle fires or fuel spillage events; they will be discussed in Section 4.7 of this report. No detailed information on the actual cause or source of the fuel leak is provided. At best, individual run reports may list "carburetor" or "fuel pump" with no additional detail.

After having evaluated the approaches discussed above, it was concluded that the only reliable source for information on fuel systems failures, particularly in enough detail to identify specific problem areas, is the Multidisciplinary Team reports. Although the adoption of a specialized police report form could produce a more rapid accumulation of data on this subject, this approach hardly seems feasible because of the limitations on available police time and because of the problems of achieving standardized reporting with non-specialist personnel.

4.5.3 Comparison of Fuel Systems Construction Practice, 1966-1968 versus 1972 Models

An "in-depth" study of fuel system design was done by Fairchild-Hiller (26) in 1969. That report contains "point by point" descriptions, with photographs, of the fuel, exhaust and electrical systems of a sample of vehicles manufactured in the years 1966 through 1968.

The majority of the vehicles studied, including the 1968's, were manufactured before the applicable Federal Motor Vehicle Safety Standard, FMVSS 301, became effective January 1, 1968. Therefore, in an effort to ascertain changes made since that date, comparative documentation on fuel system design has been carried out on similar 1972 vehicles under this contract. For the remainder of the Section it is advantageous for the reader to have a copy of the Fairchild-Hiller report (26) for ready reference to the corresponding discussion in this report.

All vehicles examined were 1972 models; they are listed in virtually the same order as in the Fairchild-Hiller report; however, a few of those models listed in Fairchild-Hiller's report are no longer in production. Similar new models have been substituted, where possible. Conversely, two new vehicles have been added because of their popularity, the Ford Pinto and the Chevrolet Vega.

Photographs and brief descriptions of fuel system features of the 1972 automobiles follow.

4.5.3.1 American Motors Gremlin: The "Rambler" as reported by Fairchild-Hiller, is no longer in production; therefore, the "Gremlin" was chosen as the American Motors' representative.

The fuel supply line passes between the transverse transmission support member and the floor pan. Rubber sleeving is not required for protection because the line is straight at this point (see Figure 4.57).

The fuel supply line still incorporates a rather long (12 in), flexible hose at the end of its run to the fuel pump. However, it no longer passes between the distributor and the engine block (see Figure 4.58).

Note also that the fuel line to the carburetor runs directly over the engine as opposed to forward and around the coolest part of the engine and then terminates at the carburetor as in the Rambler. Fuel line routing under the car was adequate. Note the smooth turns and how the fuel line runs in the protected drive shaft cavity (Figures 4.59 and 4.60). Also notice how care was taken to direct the fuel line around a sharp hazard (Figure 4.61).

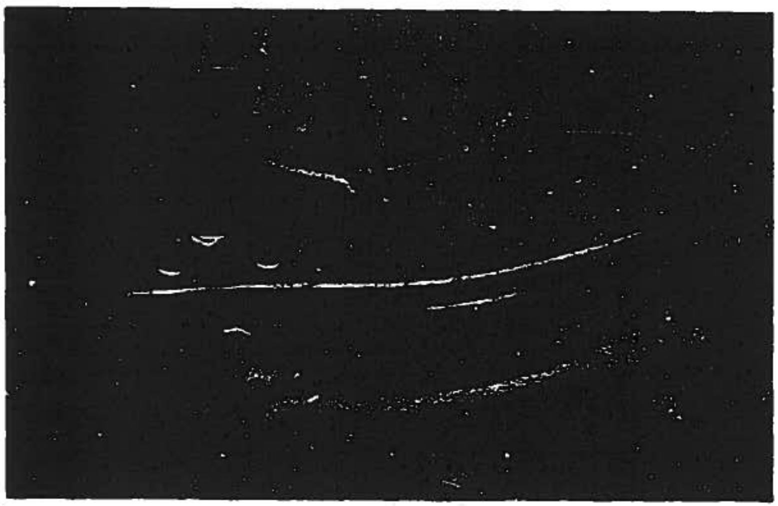


Figure 4.57. Gremlin fuel line routing near transmission.

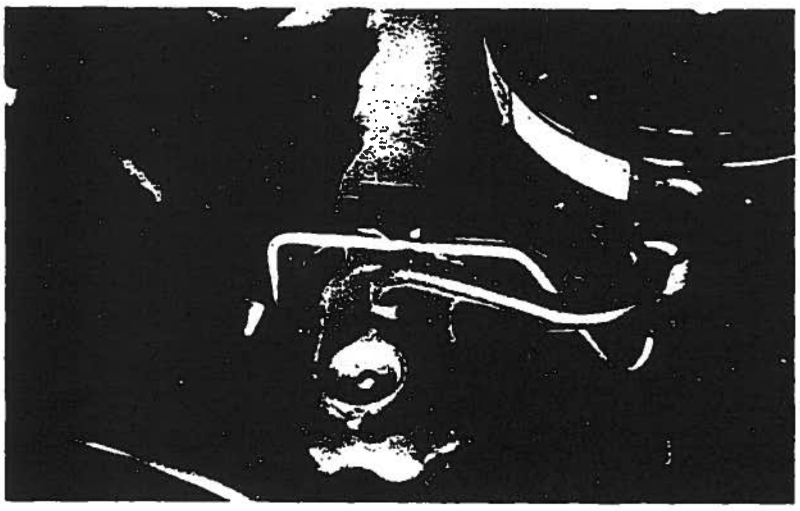


Figure 4.58. Gremlin fuel line routing at engine.

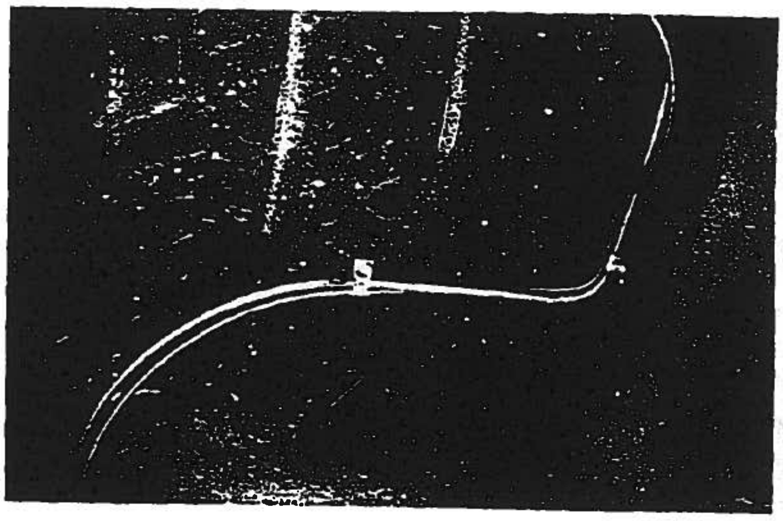


Figure 4.59. Gremlin fuel line routing from rear frame to drive shaft cavity.

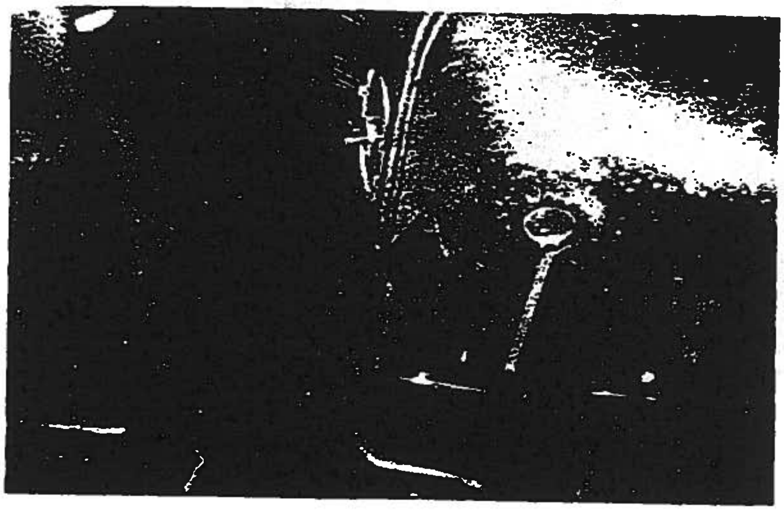


Figure 4.60. Gremlin fuel line routing in drive shaft cavity.

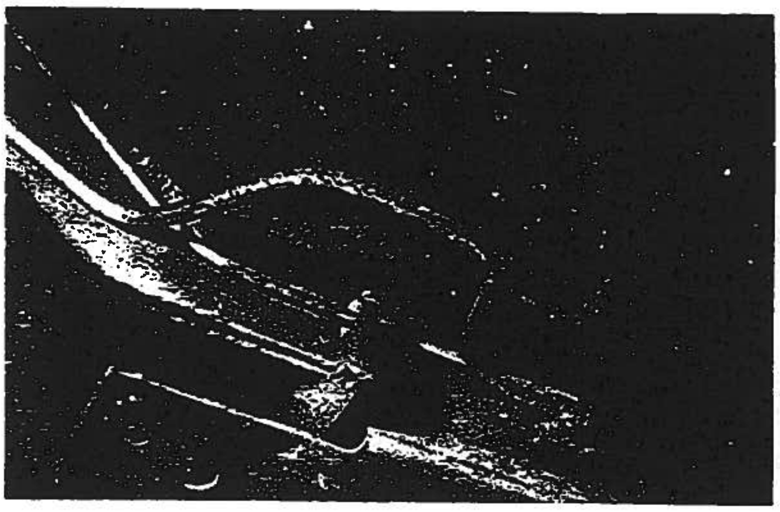


Figure 4.61. Gremlin fuel line routing around a sharp projection.

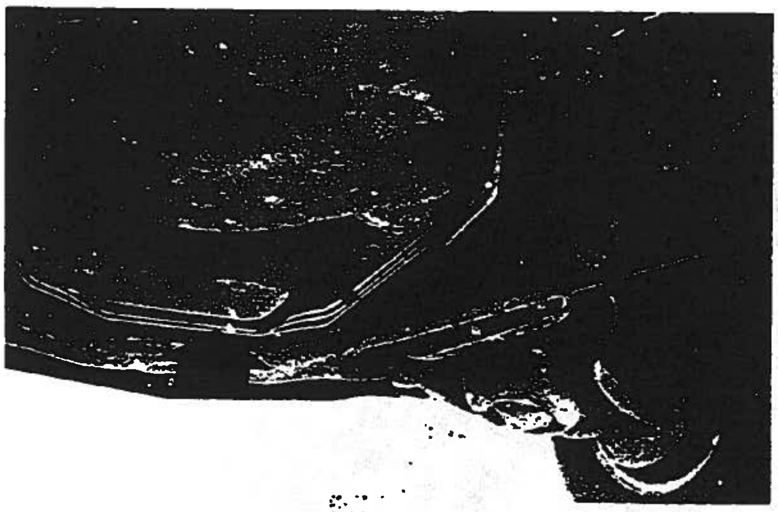


Figure 4.62. Riviera fuel line routing at engine.

4.5.3.2 Buick Riviera: The feature found in the 1967 Rivieras, which consisted of the flexible-hose fuel lines running through a punched hole in the structural member, is no longer used in the 1972's. Instead, the fuel lines run behind the transverse frame cross member under the engine and then up to the fuel pump. This method appears to provide adequate security for the line (Figures 4.62 and 4.63).

This vehicle has one unusual installation. The filler pipe is located at the left rear of the fuel tank (Figure 4.64). The filler pipe is relatively short (7 in), but it does have the added feature of convolutions, similar to those on the Oldsmobile Cutlass, at its base (Figure 4.65). There is little crush room between the fuel tank and the rear bumper (Figure 4.66), although the light cross member provides some additional protection.

Figure 4.63. Riviera fuel line routing at engine.

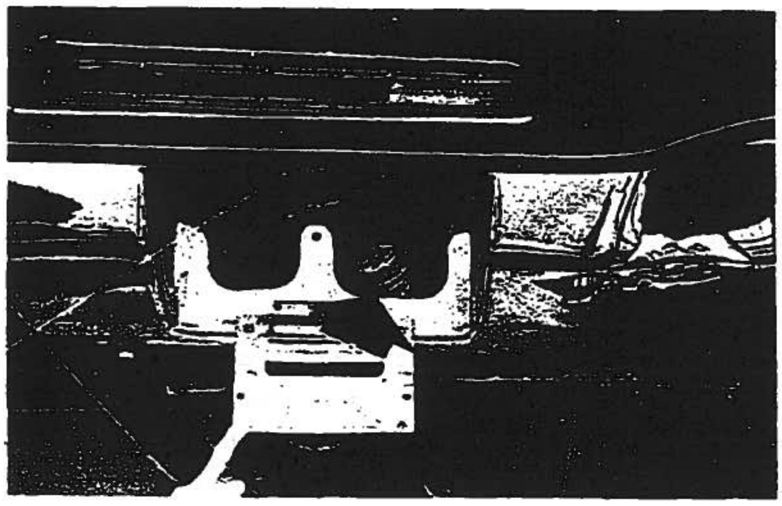


Figure 4.64. Riviera filler pipe at left rear corner of fuel tank.

Figure 4.65. Riviera filler pipe convolutions.

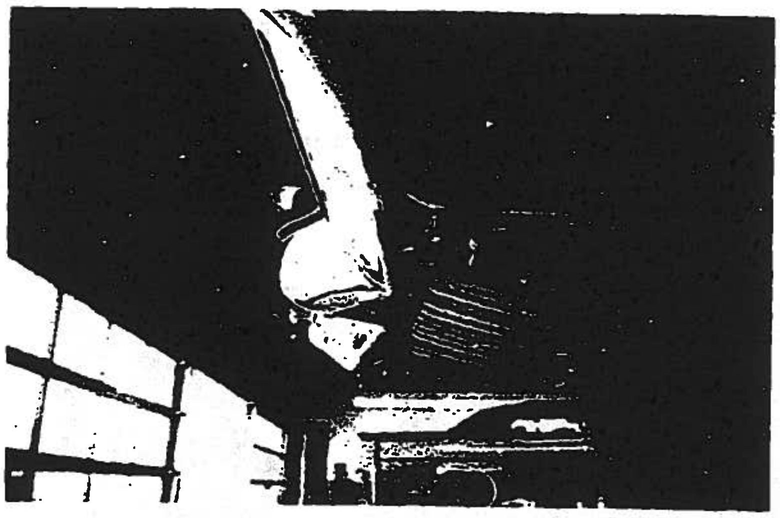


Figure 4.66. Riviera fuel tank proximity to rear bumper.

4.5.3.3 Cadillac Coupe de Ville: The filler pipe now passes over the rear frame rail as opposed to through it (Figure 4.67). With the new installation, transverse deformation of the rear rail would probably not break the connection.

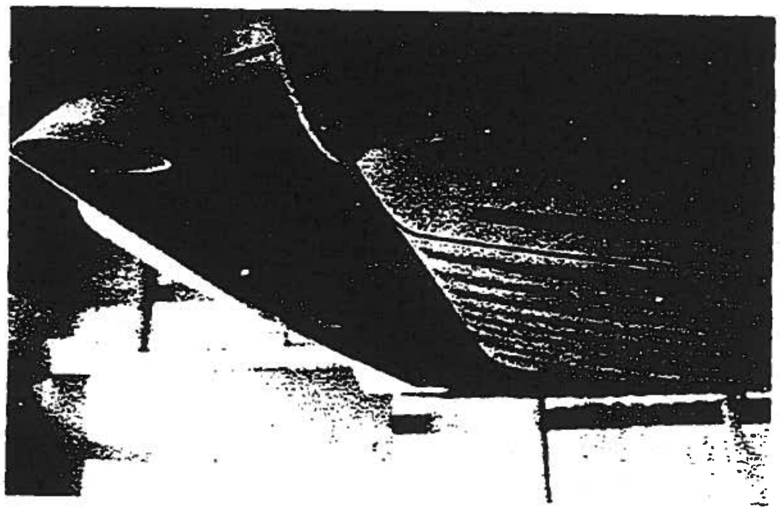


Figure 4.67. Coupe de Ville filler pipe above rear frame rail.

4.5.3.4 <u>Chevrolet Impala</u>: Figure 4.68 shows adequate fuel and vent line routing in the vicinity of the fuel tank and differential.

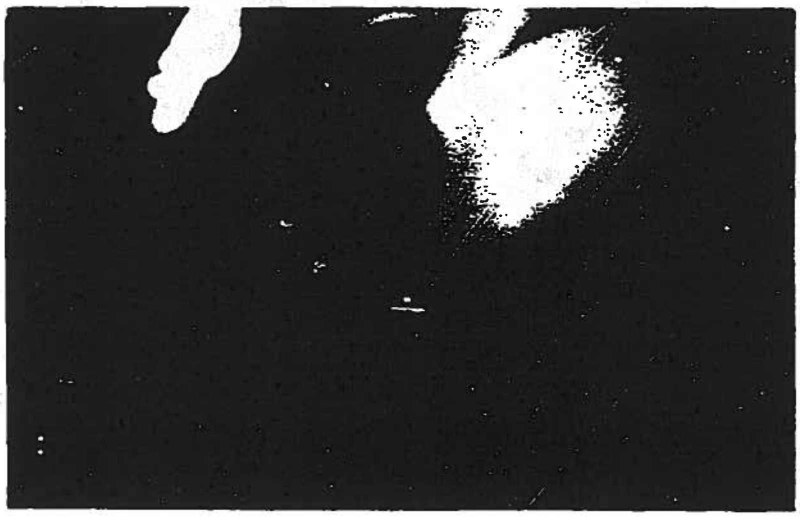


Figure 4.68. Impala fuel and vent line routing.

4.5.3.5 <u>Chevrolet Vega</u>: Although the Vega was not in production in 1969, a few comments on it and the Ford Pinto have been included because these vehicles are members of the new class of American-made sub-compacts.

Careful consideration of fuel line routing appears to be in evidence. Figures 4.69 and 4.70 show the fuel line and return line as they follow the floor pan of the car. Note the wire protectors around the lines in Figure 4.69.

Some improvement in fuel tank protection might be possible. The fuel tank has little crush-room between the tank and rear bumper (Figures 4.71 and 4.72). Also note the short length of the filler pipe and the lack of convolutions at its base (Figure 4.72).

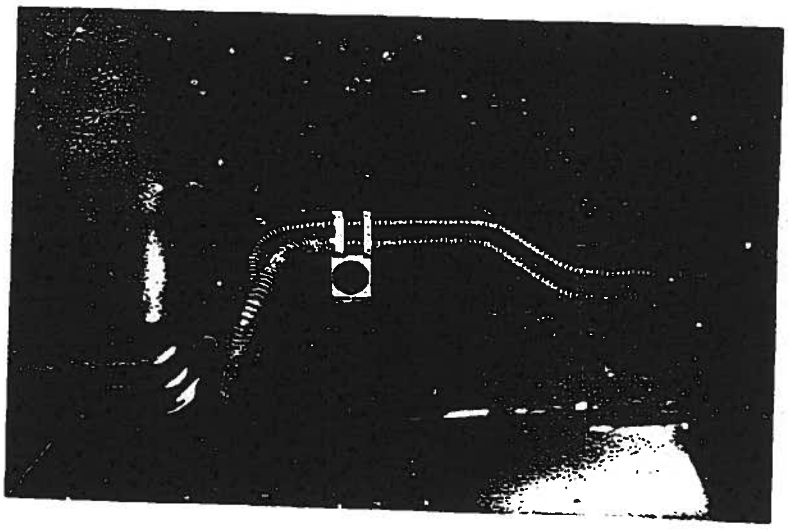


Figure 4.69. Vega fuel line routing.

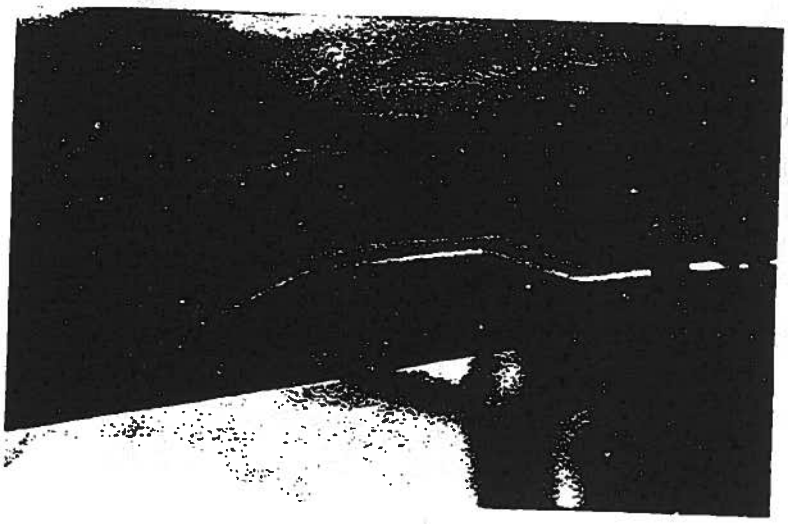


Figure 4.70. Vega fuel line routing.

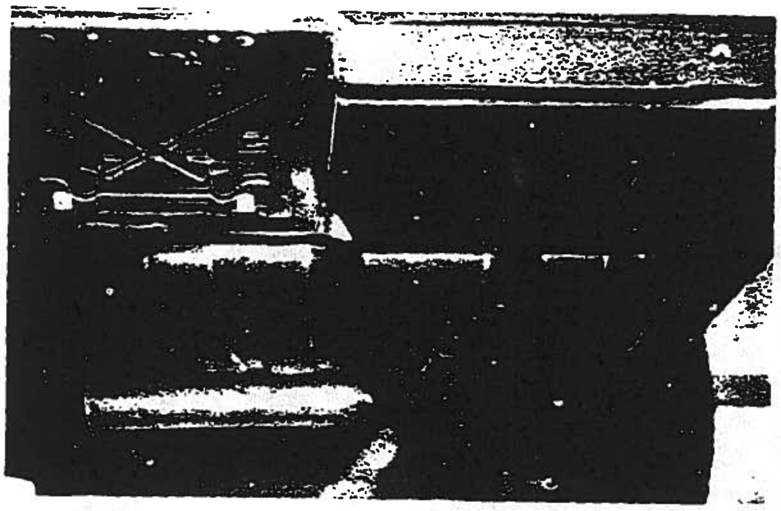


Figure 4.71. Vega fuel tank location.

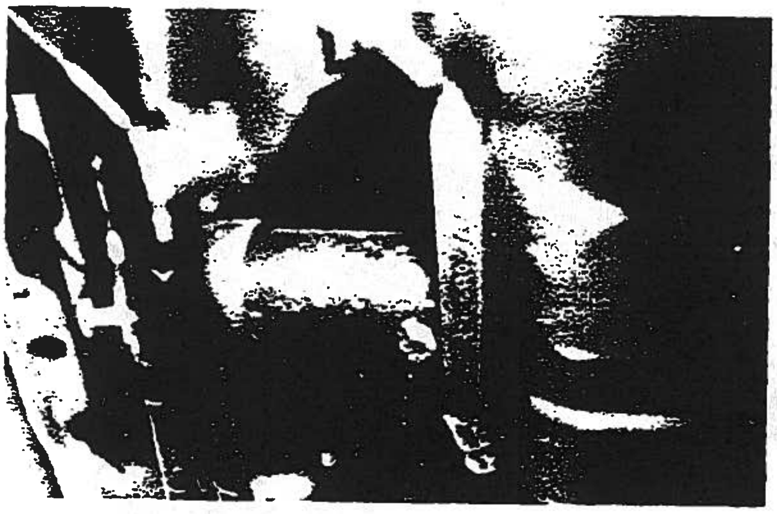


Figure 4.72. Vega filler pipe.

It was also observed that a three-conductor electrical wire is located in a small space between the flange of the fuel tank and the frame (Figure 4.73). In a crash situation, if the frame were pushed against the fuel tank, the wire would be exposed to damage. A resulting electrical short or sparks could ignite any spilled gasoline in the vicinity.

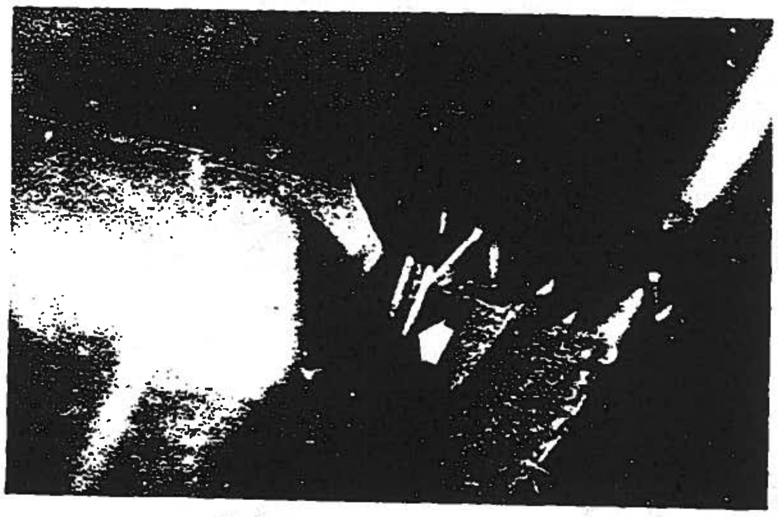


Figure 4.73. Vega electrical wire between fuel tank and frame.

4.5.3.6 Chrysler New Yorker: Figure 4.74 shows the fuel tank location to be virtually identical with that of the 1968 New Yorker. It has the same difficulty with the rear crossrail: the flanged edge is close to the tank so that rear impact could drive the flange against the tank and possibly cause rupture.

Figure 4.75 shows the fuel line sagging below its protective flange. The line could be snagged causing fuel spillage.

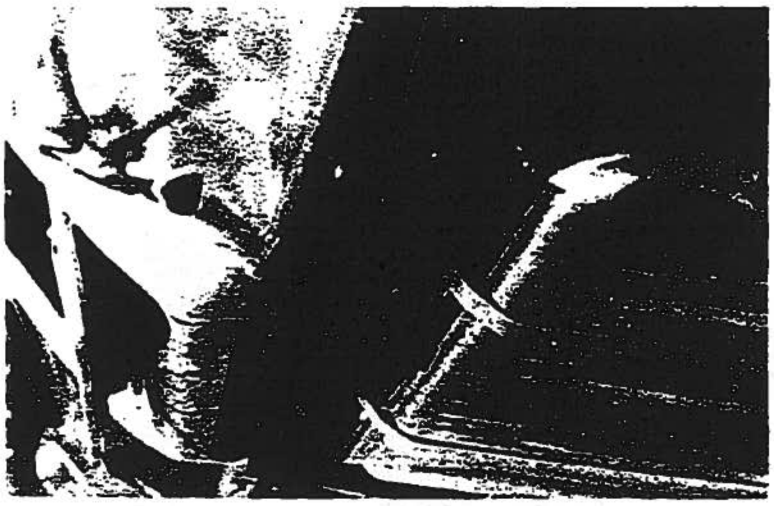


Figure 4.74. New Yorker fuel tank proximity to rear crossrail.

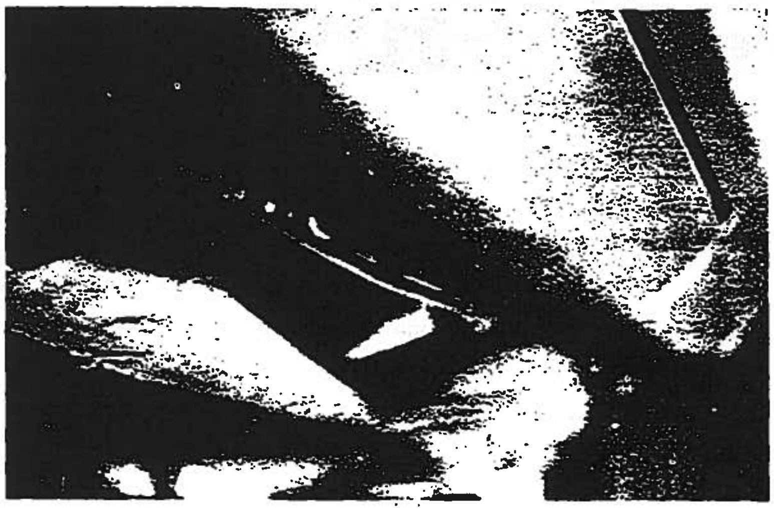


Figure 4.75. New Yorker fuel line sag.

4.5.3.7 Dodge Coronet: Figure 4.76 shows unprotected fuel lines passing through a punched hole in a frame cross member.

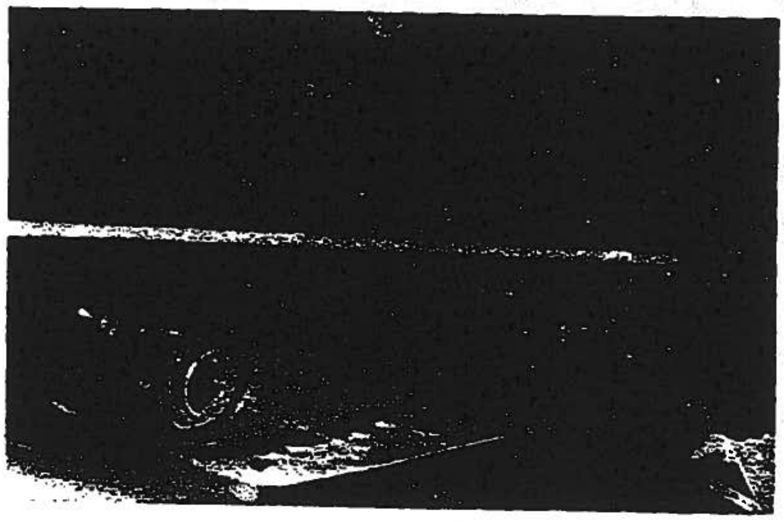


Figure 4.76. Coronet fuel line passing through structural member.

Figure 4.77 shows a new filler pipe design and adequate crush room between the rear bumper and fuel tank.

4.5.3.8 Dodge Dart "340": Figure 4.78 shows the two longitudinal retainer straps supporting the fuel tank. This retainment method is an improvement over that of the 1967 Dart which incorporated a single transverse strap for the same purpose. Note the relative positions of the spare wheel well, the back bumper, and the fuel tank. A relatively minor impact that is sufficient to deform the floor pan could cause damage to the fuel tank because the crush spaces are small (Figure 4.79).

Figure 4.80 shows the fuel line which has the same configuration as that in the 1967 Dart. Distortion in this area could rupture the fuel line.

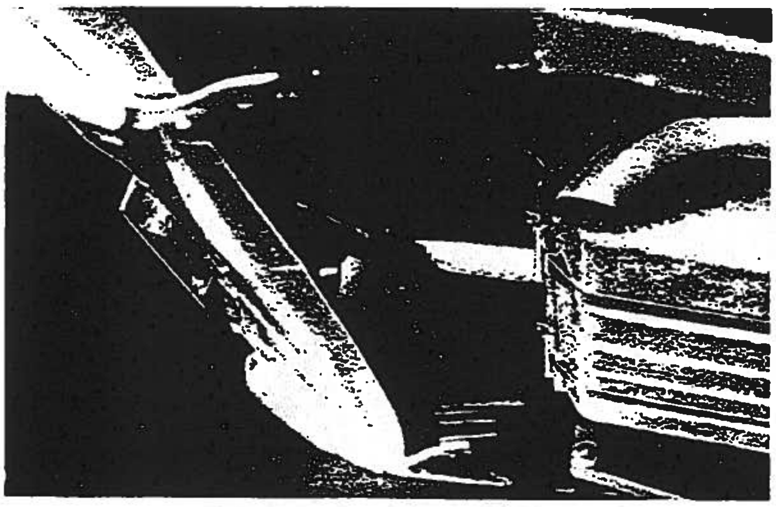


Figure 4.77. Coronet filler pipe.

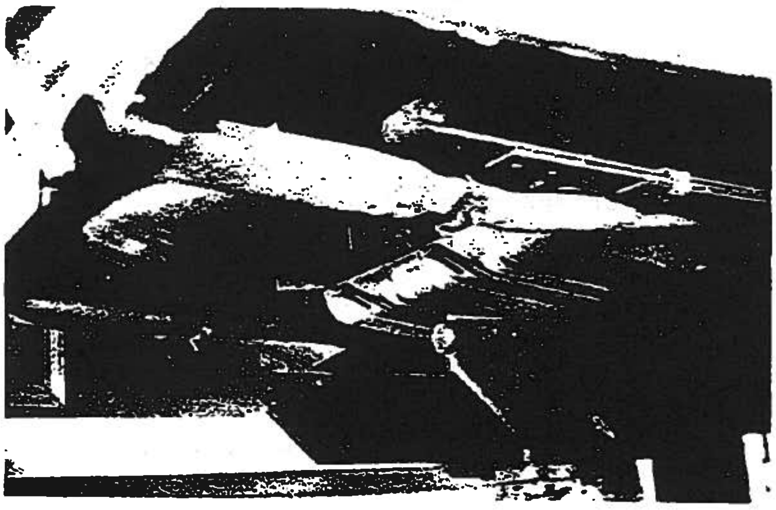


Figure 4.78. Dart fuel tank location.

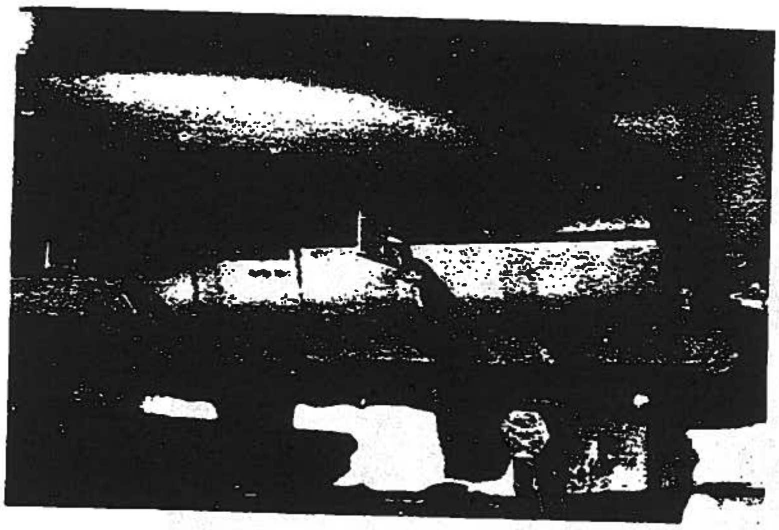


Figure 4.79. Dart spare wheel well proximity to fuel tank.

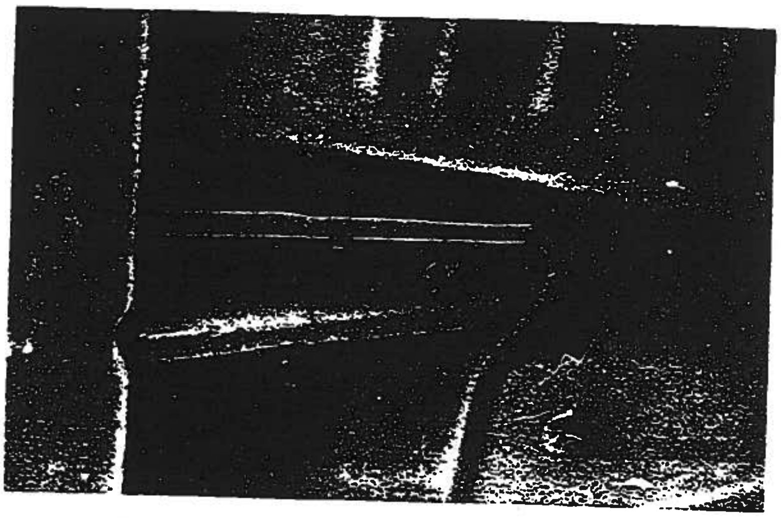


Figure 4.80. Dart fuel line routing.

Figure 4.81 shows the filler pipe inside the trunk. in a rear-end crash, the pipe would be subject to impact by articles carried in the trunk.

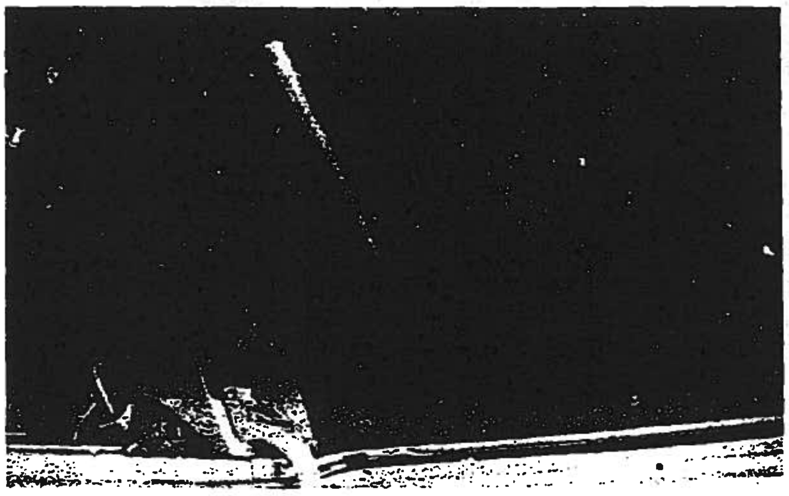


Figure 4.81. Dart filler pipe location.

The carburetor shown in Figure 4.82 is more elaborate than the one shown in the Fairchild-Hiller report, because the 1972 Dart is a special, high-performance version. The fuel line appears to be well enough located not to be a hazard.

4.5.3.9 Dodge Polara: Figure 4.83 shows the location of the fuel tank near the rear bumper of the car. This location increases rear impact vulnerability.

The relative closeness of the left frame member to the fuel tank is shown in Figure 4.84. This proximity is not considered dangerous since the web is adjacent to the tank.

The treatment of the fuel line where it crosses above the exhaust system intermediate pipe gooseneck is satisfactory in both the 1966 and 1972 Polaras (Figure 4.85).

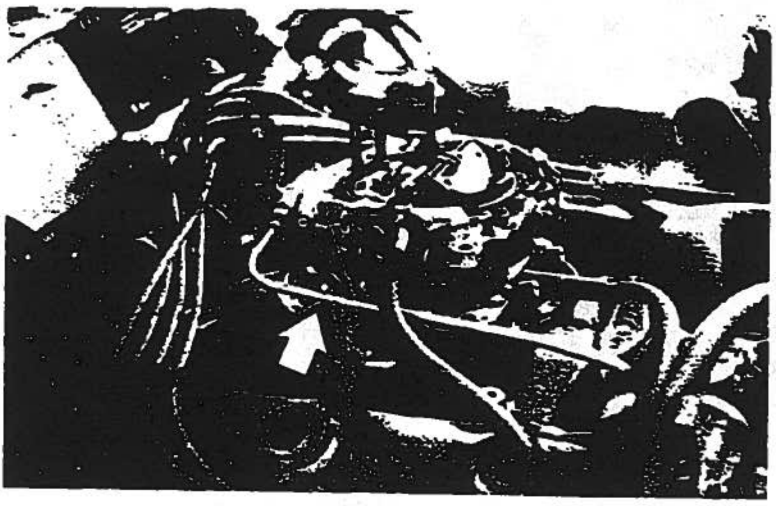


Figure 4.82. Dart fuel line routing at carburetor.

Figure 4.83. Polara fuel tank proximity to rear bumper.

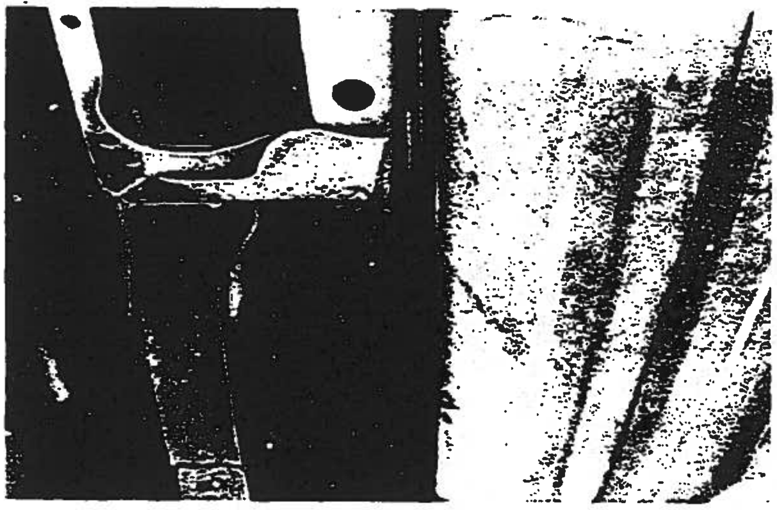


Figure 4.84. Polara fuel tank relative to left frame member.

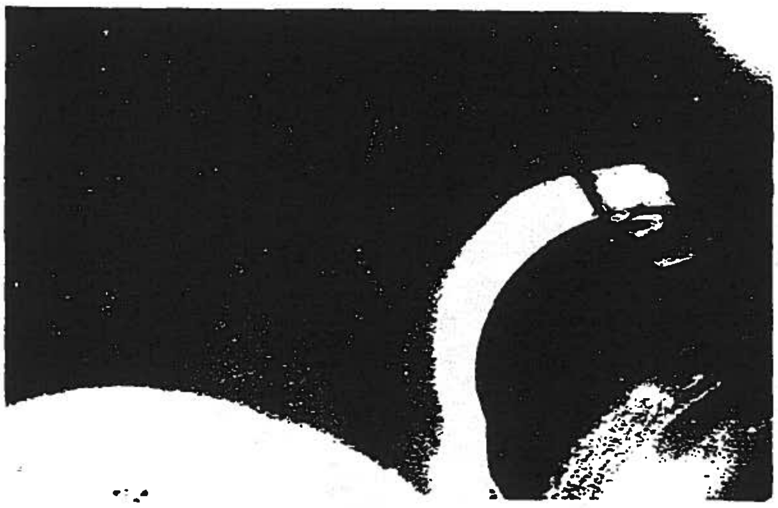


Figure 4.85. Polara fuel line routing near exhaust pipe.

Figure 4.86 shows the fuel lines routed under the right side frame member. If the car were to hit "high center," on that side, fuel line damage could occur.

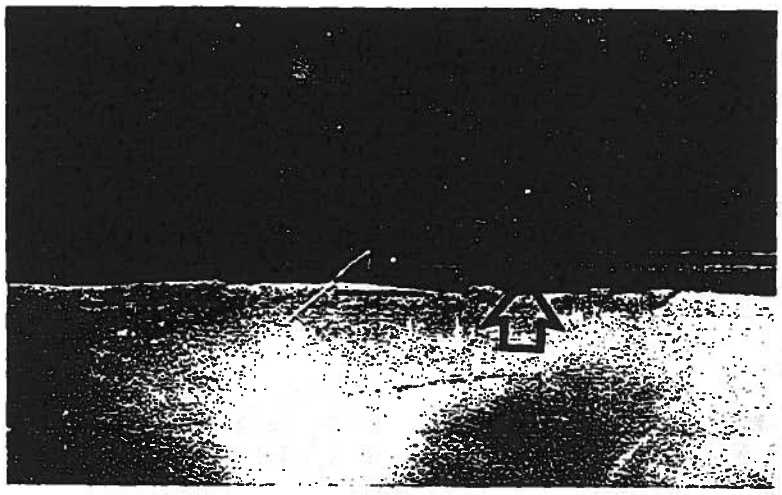


Figure 4.86. Polara fuel line routing along right side frame member.

4.5.3.10 Ford Country Squire Station Wagon: The Fairlane station wagon, as reported by Fairchild-Hiller, is no longer in production. Therefore, a Ford Country Squire Station Wagon was chosen for comparison. The Country Squire's fuel tank is located under the vehicle in the same manner as in the Ford Galaxie (Figure 4.88).

4.5.3.11 Ford Galaxie 500: Figure 4.87 shows an unusual method of routing the fuel line through the left front wheel well. (Note the relationship of the tire and the fuel line.) A direct impact on the left front of the car could deform the wheel enough to cut the line. One improvement appearing in the same photograph is the rubber grommet which protects the line as it passes through the engine compartment side wall.

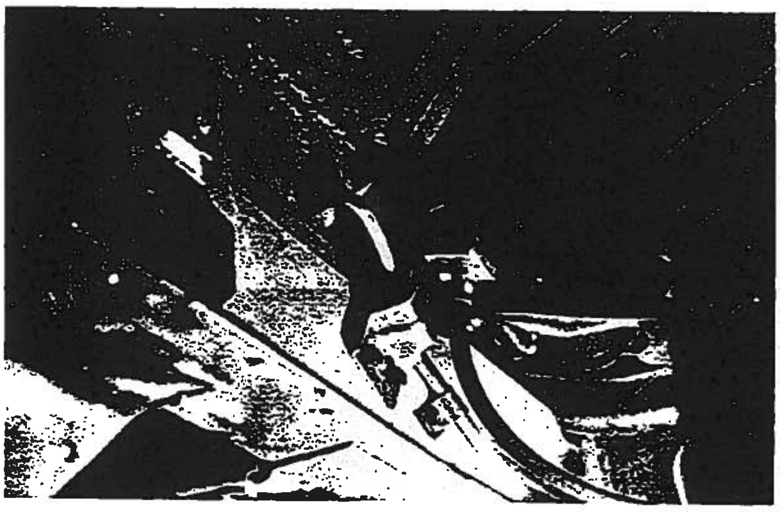


Figure 4.87. Ford Galaxie 500 fuel line routing through the left front wheel well.

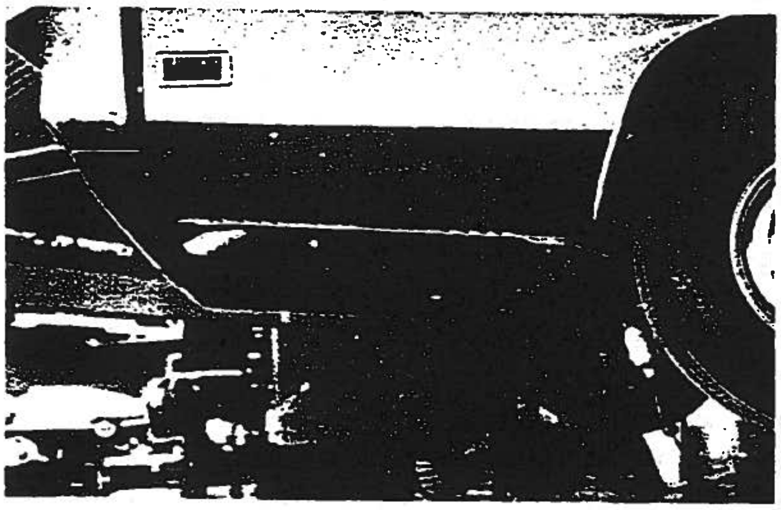


Figure 4.88. Ford Galaxie 500 fuel tank location.

Figure 4.88 shows the fuel tank located in a position of relative safety parallel to the rear axle, between the sheels. Note the ample crush room between the rear bumper and the fuel tank. The floor pan of the trunk provides additional strength, but it could transmit forces directly to the tank.

Figure 4.89 shows the filler pipe located in the left rear fender well.

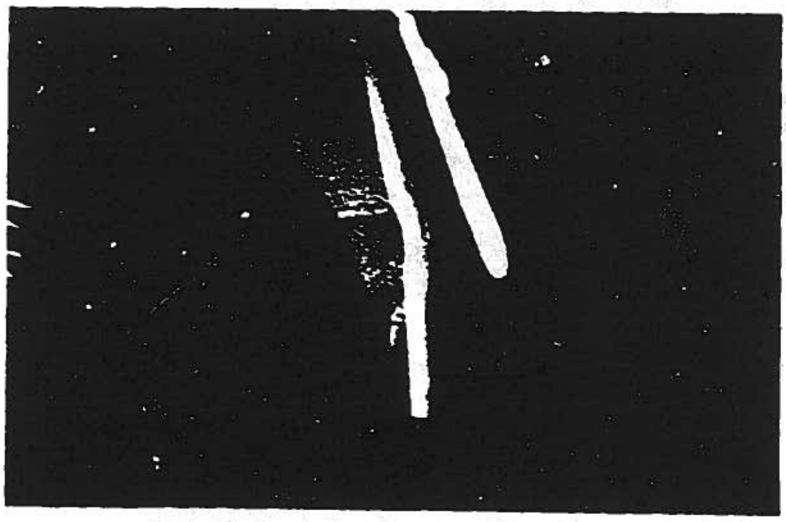


Figure 4.89. Ford Galaxie 500 filler pipe location.

4.5.3.12 Ford Mustang: Figure 4.90 shows the fuel tank and its position relative to the rear fender. There is not enough crush space to give much protection from a rear-end collision.

Figure 4.91 shows the short filler pipe in the rear of the trunk. It is exposed to damage from articles in the trunk as well as from rear-end collisions. This installation also appears to be vulnerable to shearing at the filler neck-tank junction.

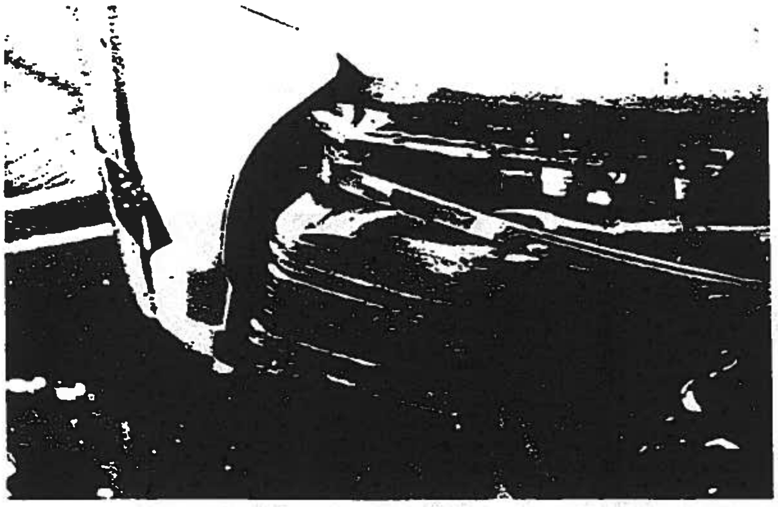


Figure 4.90. Mustang fuel tank location.

Figure 4.91. Mustang filler pipe.

The fuel level sensor and fuel line connections at the fuel tank are shown in Figure 4.92. They are located on the left end of the fuel tank. For a reference, compare the longitudinal support strap shown in Figure 4.92 with that in Figure 4.90. There is a possibility that the connections here may be damaged by rocks thrown up by the tires, low brush, etc.

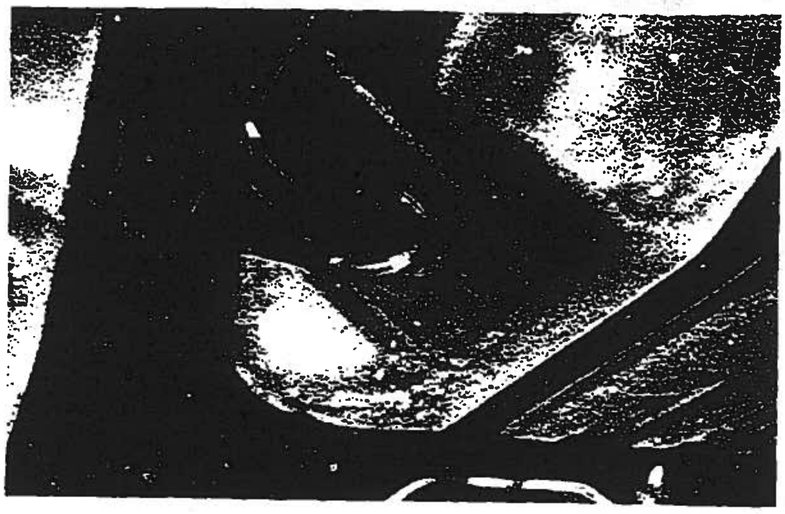


Figure 4.92. Mustang fuel line and fuel level sensor connections at fuel tank.

Figure 4.93 shows the left rear tire, the main longitudinal frame member, and the fuel line routing through the wheel well. It would be more protected if it ran along the inside of the frame rather than on the outside.

The fuel line is routed just inside the rocker panel flange on the left side of the vehicle (Figure 4.94) and has little protection from side impact.

The fuel line runs the entire length of the rocker panel and then up into the left front wheel well (Figure 4.95). At this point, it is susceptible to damage from rocks

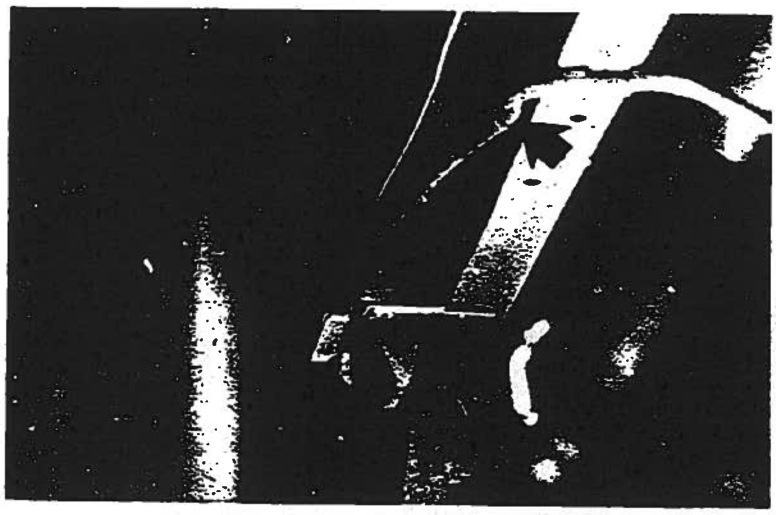


Figure 4.93. Mustang fuel line routing in left rear wheel well.

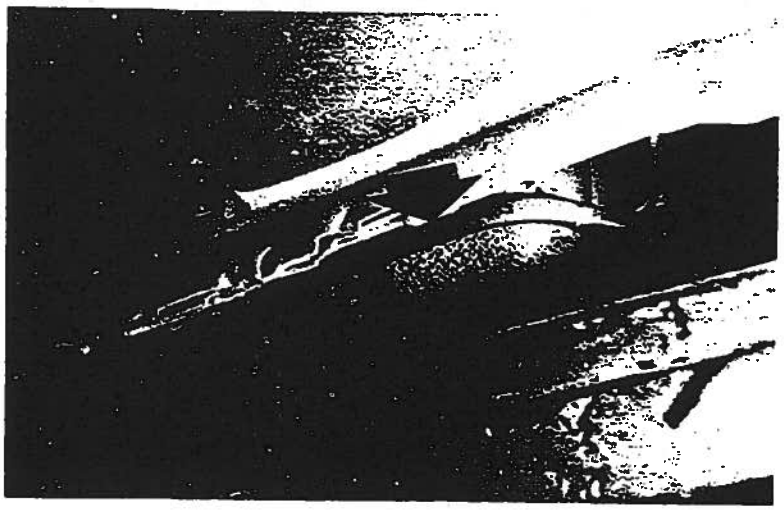


Figure 4.94. Mustang fuel line routing under left rocke panel.

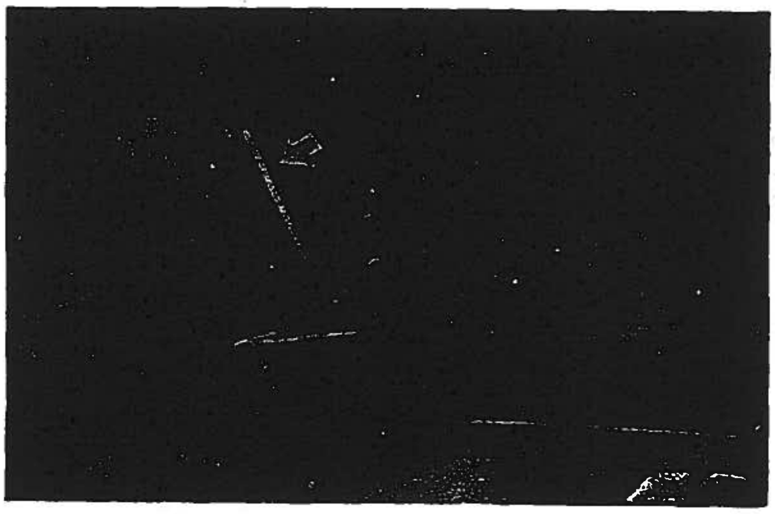


Figure 4.95. Mustang fuel line routing in left front fender well.

picked up by the tire. Also, the wheel could be pushed into the line if the car were impacted on the left front. A couple of preferred construction techniques can be seen in the same picture. First, the fuel line is protected by an abrasion resistant wire coil where it makes a sharp turn in the foreground of the picture. Second, where the fuel line passes through a punched hole, it is protected by a rubber grommet.

4.5.3.13 Ford Pinto: The Pinto has little crush room between the fuel tank and rear bumper (Figure 4.96), an inherent problem due to the small size of the car. However, the fuel tank could be located farther forward.

The long filler pipe, shown in Figure 4.97, is located in the left fender well. It has little protection from impact, and, since it is attached to the fuel tank with a rubber grommet assembly, it could fairly easily be pulled out of the tank.

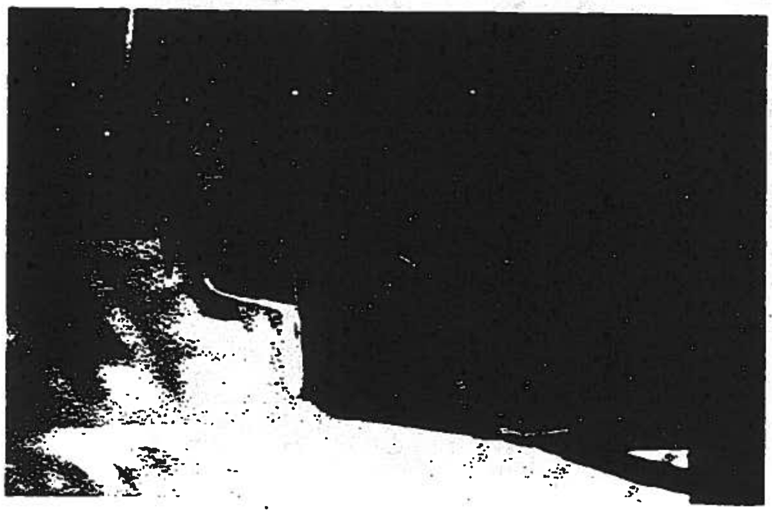


Figure 4.96. Ford Pinto fuel tank location.

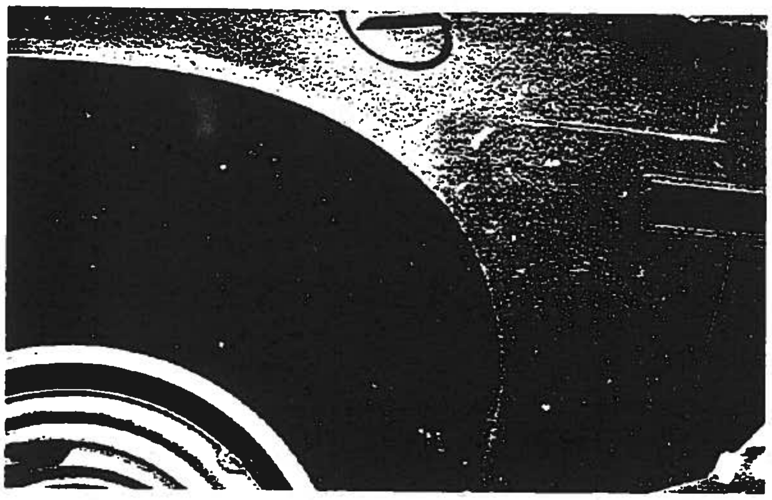


Figure 4.97. Pinto filler pipe location in left rear fender well.

4.5.3.14 Fiat 124 Sedan Special: The Sedan Special has its fuel tank located inside the trunk in the right fender well (Figure 4.98). It has no protection from articles in the trunk and little protection from external impact on the right rear fender.

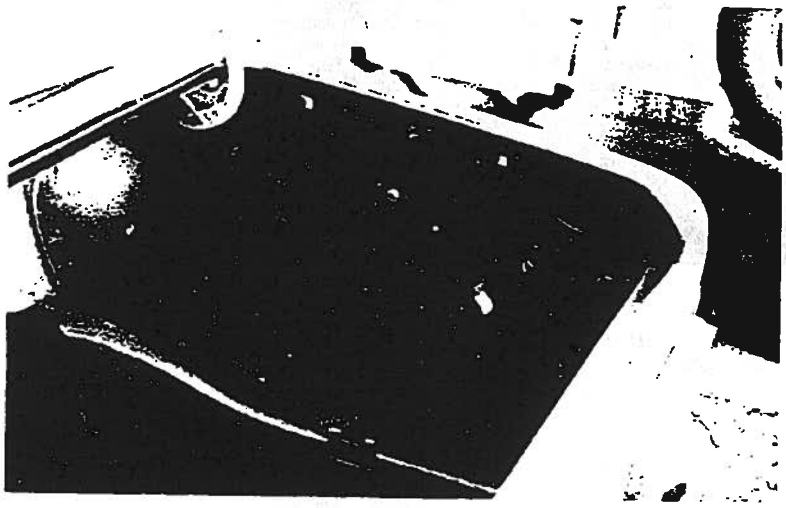


Figure 4.98. Fiat 124 Sedan Special fuel tank location.

A strong impact on the right rear quarter panel could cause the fuel tank to break its one apparent mounting strap (Figure 4.99) and spill gasoline inside the trunk. It should be noted that the running light mounted at the side of the fuel tank could provide an ignition source. A broken bulb or cut wires could produce a spark which could ignite the fuel (Figure 4.100).

Figure 4.101 shows the rear of the back seat and its proximity to the fuel tank and fuel lines. The rear covering of the seat appeared to be pressed paper board. It would offer little protection from fuel penetration or fire.

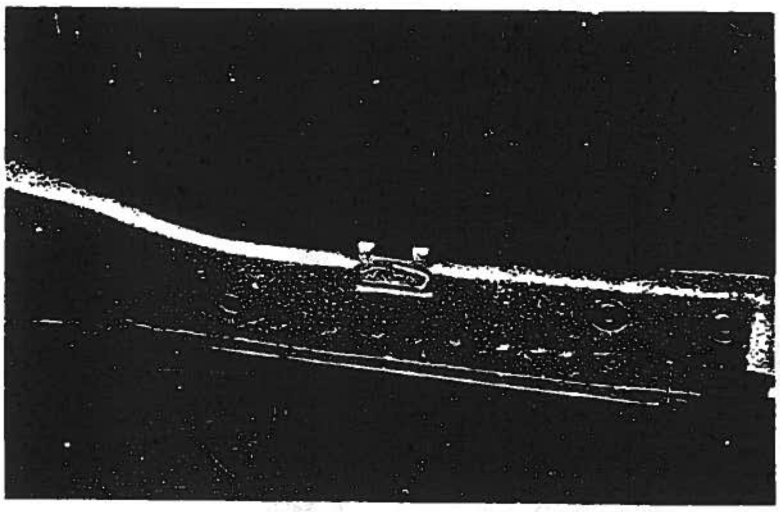


Figure 4.99. Fiat 124 Sedan Special fuel tank mounting strap location.

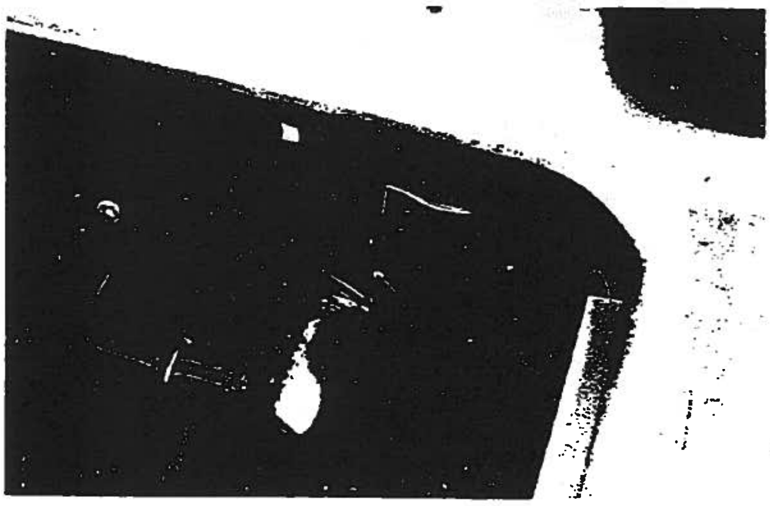


Figure 4.100. Fiat 124 Sedan Special running light location relative to fuel tank.

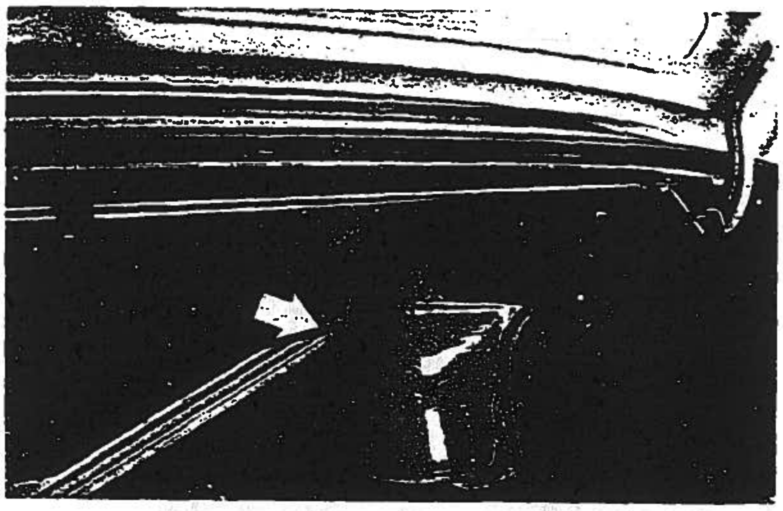


Figure 4.101. Fiat 124 Sedan Special fuel line routing.

<u>4.5.3.15 Fiat 128 4-door</u>: Figure 4.102 is a view of the filler pipe-vent assembly located in the left side of the trunk. It is unprotected from articles in the trunk.

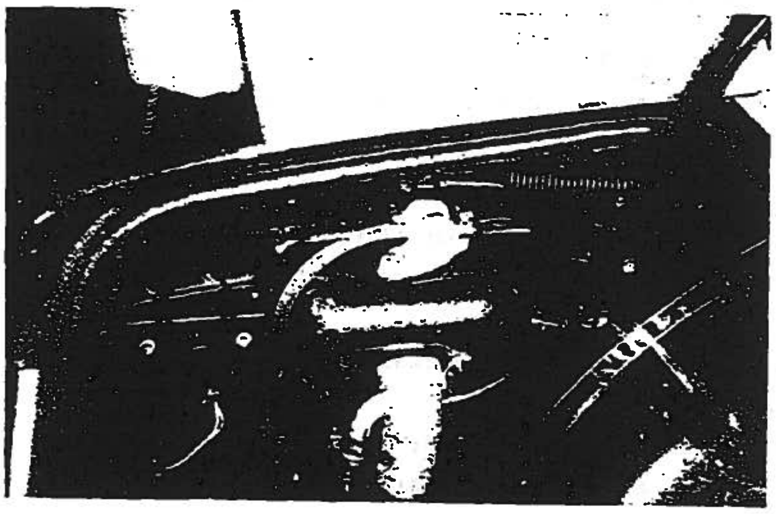


Figure 4.102. Fiat 128 filler pipe assembly.

4.5.3.16 Fiat 124 Sport: Figure 4.103 shows a metal guard protecting the filler pipe where it connects with the fuel tank under the vehicle.

Figure 4.103. Fiat 124 Sport filler pipe protective guard.

4.5.3.17 Fiat 850 Roadster: Figure 4.104 shows little or no change in fire wall design of the vehicle. The 850 coupe was not available for study.

4.5.3.18 Mercury Monterey: Figure 4.105 shows the fuel line in the same position as in the 1966 Monterey. It is bent around the distributor and rests against the spark plug leads.

A protective rubber cap covering the track bar bolt is shown in Figure 4.106.

4.5.3.19 Oldsmobile Cutlass: Figure 4.107 shows ample crush-space between the fuel tank and rear bumpers as well as convolutions at the base of the filler pipe. This design is basically the same as that of the 1968 Cutlass.

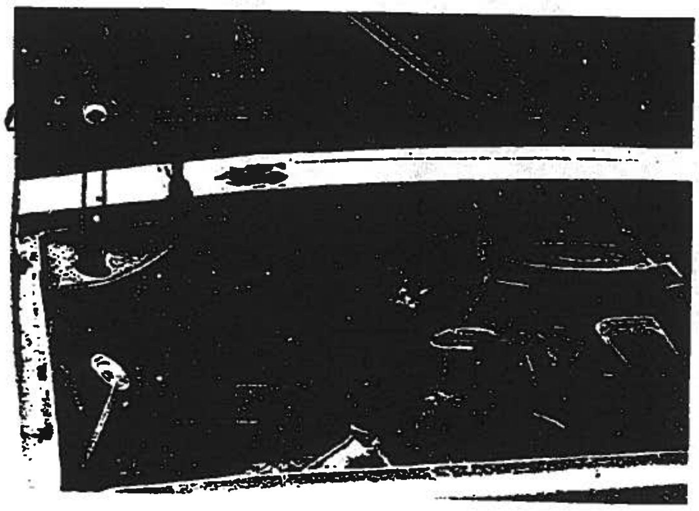


Figure 4.104. Fiat 850 Roadster front fire wall.

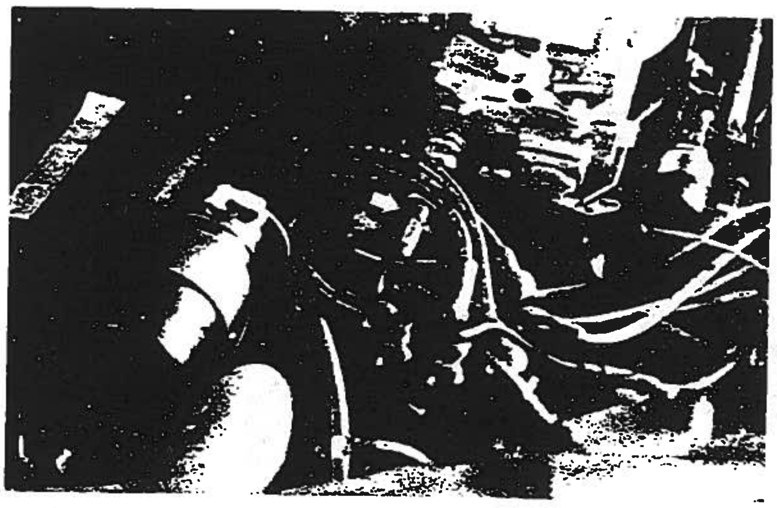


Figure 4.105. Monterey fuel line routing at carburetor.

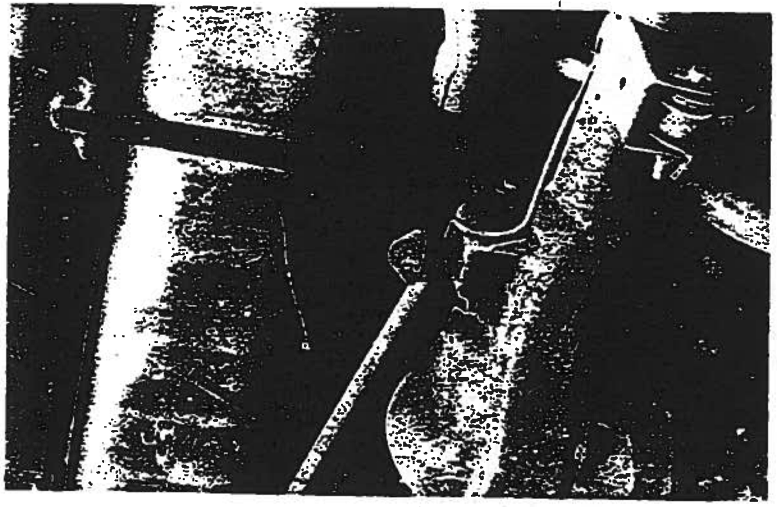


Figure 4.106. Monterey fuel tank location and track bar bolt.

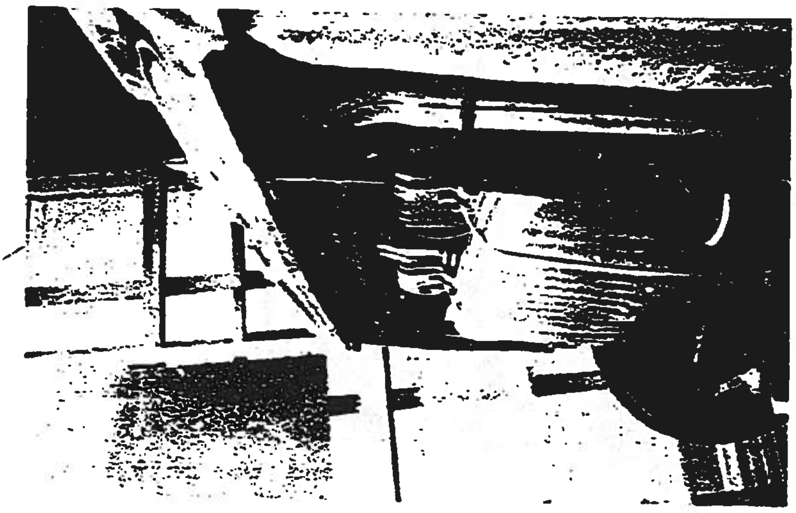


Figure 4.107. Oldsmobile Cutlass fuel tank location.

4.5.3.20 Pontiac LeMans: No change has been made to protect the fuel line where it passes through the punched hole in the left front frame member (Figure 4.108).

Figure 4.108. Pontiac LeMans fuel line routing through frame member.

Figure 4.109 shows adequate crush-space between the fuel tank and rear bumper and convolutions at the base of the filler pipe.

4.5.3.21 Toyota 2-door hardtop: There have apparently been few changes made in fuel system design. The luggage compartment floor is still the top of the fuel tank (Figure 4.110). Fairchild-Hiller identifies the inadequacies in this type of design in the discussion on the 1966 Mustang.

Figure 4.111 is a view of the small crush-space between the rear of the fuel tank and the rear bumper.

The fuel line is routed beside the driveshaft in the driveshaft tunnel. This arrangement appears to be an adequately protected location (Figure 4.112).

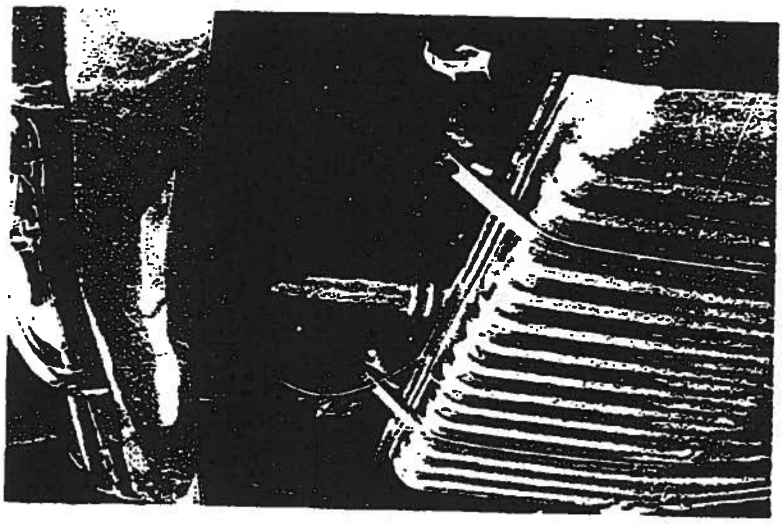


Figure 4.109. LeMans filler pipe.

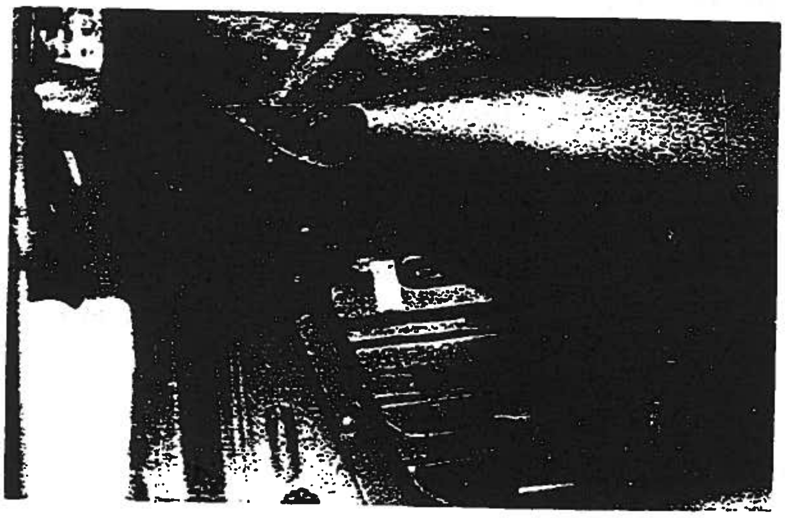


Figure 4.110. Toyota luggage compartment.

Figure 4.111. Toyota fuel tank location relative to rear bumper.

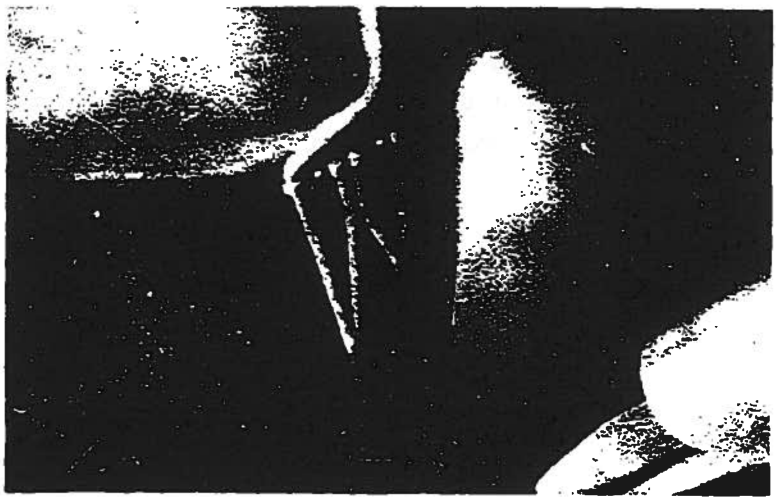


Figure 4.112. Toyota fuel line routing.

4.5.4 Conclusions and Recommendations

Although this effort was purely a documentation of existing practices in the construction of fuel systems, the following conclusions seem appropriate:

1. Adequate information is not available to compare the merits of the crash-insensitive-fuel approach with the improved fuel-containment approach.
2. Current fuel-system integrity cannot be deduced from data presently supplied by salvage yard surveys, accident reports, or fire department run reports.
3. Salvage yard surveys provide no useful information other than single case examples of crash-induced mechanical failure caused by unknown forces.
4. Although automotive fuel systems may perform adequately to meet the requirements of FMVSS 301, in many particulars they do not exemplify cautious engineering design. Similarly, no extensive effort appears to be made to attempt to prevent fuel penetration into the passenger compartment in some failure modes.

In view of Conclusion 4, it is recommended that more definitive engineering design criteria be established to minimize potential hazards from fuel system failures.

4.6 FIRE EXTINGUISHER TESTS

During the previous contract, FH-11-7303, it became evident that many vehicle interior fires could be extinguished, or at least controlled, during the incipient stages by means of a small, portable extinguisher. For this reason, the recommendation was made that a small portable fire extinguisher be required as standard equipment on every new automobile. As a follow-up to this recommendation, one of the tasks under the present contract, FH-11-7512, called for a more substantive evaluation of the effectiveness of a small portable extinguisher in the hands of the average motorist.

4.6.1 Test Program

The utility of a fire extinguisher for a particular application depends on the type of fire, the type of extinguisher and extinguishing agent, the level of competence in the user, and the environmental conditions. Thus, a test program to evaluate fire extinguishment capabilities should give consideration to all of those variables.

4.6.1.1 Equipment: The principal agents in commercially available, portable fire extinguishers applicable to vehicle fires include carbon dioxide, foam, halogenated hydrocarbon and dry chemicals. A cost effectiveness evaluation of the agents suitable for the more typical vehicle fires from the standpoint of extinguishing mechanisms and general discussions with manufacturers of portable fire extinguishers revealed that a small, dry chemical fire extinguisher showed the most promise. Consequently, the fire extinguisher chosen for these tests was a 2-1/2 lb capacity, precharged dry chemical unit (about 3 in in diameter and 12 in long). The control handle and discharge nozzles were detachable so that they could be transferred readily to precharged replacement cylinders. Figure 4.113 shows the precharged cylinder, the control handle, discharge nozzle unit and the standard mounting bracket. The mounting bracket also serves as a safety guard against accidental discharge of the extinguisher during storage.

The applicable types of commercially available dry chemical agents include sodium bicarbonate, potassium bicarbonate, potassium chloride, mono-ammonium phosphate, and a combination of urea-potassium bicarbonate. Traditionally, dry chemical agents have been "approved" only for hydrocarbon liquid fuel and gaseous fires (Class B fires) and for fires which are electrical in origin (Class C fires). However, the more recent introduction of the mono-ammonium phosphate compounds, which upon decomposition in the fire produce a solid having a fire-retarding effect, has resulted in the approval of this agent for surface fires in combustible solids (Class A). Since the typical vehicle fire may include liquid fuel fires, or solid fires, or a combination of both, a dry chemical charge of mono-ammonium phosphate was chosen as the extinguishing agent for the tests.

The 2-1/2 lb capacity mono-ammonium phosphate extinguisher chosen for the tests carries an Underwriters Laboratory rating of 5:BC. This designation means that the extinguisher is approved for use on hydrocarbon fires (Class B) and electrical fires (Class C) and that the "average operator" should be able to extinguish a fire of at least 5 sq ft in size. However, although the 2-1/2 lb charge of mono-ammonium phosphate is not large enough to extinguish the existing standard Underwriters Laboratory Class A (solid fuel) test fire, U-L has approved the use of the agent for Class A, B and C fires.

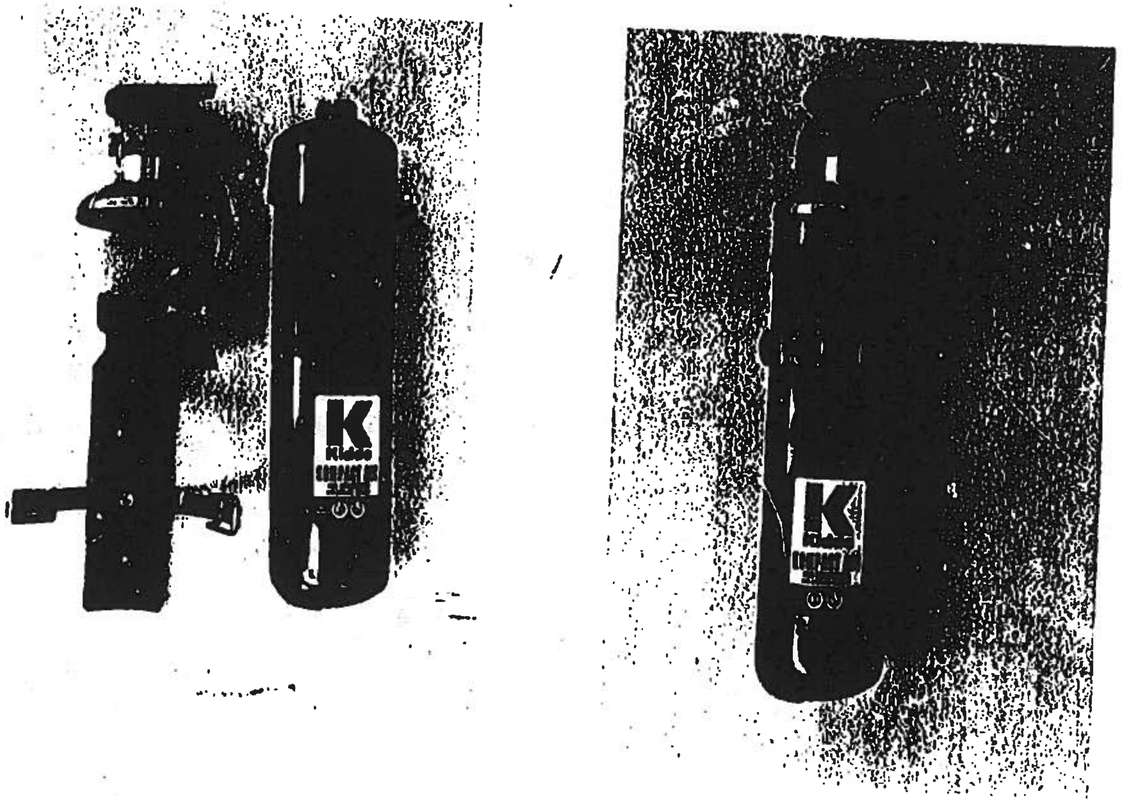


Figure 4.113 Dry chemical fire extinguisher: mounting bracket, discharge nozzle with control handle, and precharged cylinder (left), fully assembled extinguisher (right).

4.6.1.2 Types of test fires: Two types of fires were used during the fire extinguishment tests, a 5 sq ft pan fire in which commercial grade gasoline was the fuel and a simulated vehicle seat fire. Both of these test fires were considerably more severe than what would be expected in the typical hydrocarbon fire in an engine compartment or a fire in the upholstery and underlying cushion of an actual vehicle. No attempt was made to carry out a more realistic simulation of vehicle fires which obviously would have been a costly undertaking. The object of the tests was not to demonstrate the utility of the selected fire extinguisher on small fires since this application is already well established by the U-L rating which applies to an "average operator." Rather, the object was to assess the ability of completely uninstructed or untrained personnel to utilize the capabilities of the extinguishers effectively.

The pan in which the gasoline was contained was square, having a surface area of 5 ft^2 and a depth of 4 in. Figure 4.114 shows the pan before a given test sequence. The bottom of the pan was covered with about 3 in of water, and about 1/2 in of gasoline was added on top of the water. This amount of fuel is sufficient to give a pre-burn time of 30 sec, which is ample time for the fires to reach a state of vigorous burning and to heat the metal edges of the pan to a temperature hot enough to constitute a re-ignition potential. After the 30 sec of preburn, enough fuel is left for about another minute of burning which is adequate for the extinguishment attempt. It should be noted that the U-L test procedure for rating fire extinguishers calls for a preburn time of one min. However, based on our observations on the vehicle interior fires it was concluded that the typical vehicle interior fire could be detected and action initiated within 30 sec. Figure 4.115 shows a test pan fire with gasoline just prior to initiation of extinguishment efforts.

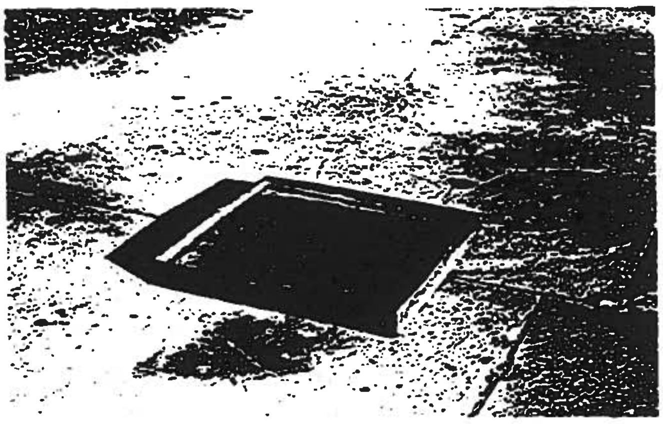


Figure 4.114. Fuel pan for gasoline fire tests.

Figure 4.115. Gasoline fire immediately before extinguishment was attempted.

The typical vehicle seat fire presents a somewhat more stubborn extinguishment problem. The major difficulty arises from the infiltration of the fire into the lower layers of the seating materials beyond the penetration range of the dry chemical extinguishing agent. A review of test fires used by Underwriters Laboratories, Factory Mutual and other agencies revealed that excelsior packings are frequently employed for tests on deep-rooted, solid fires. For this reason, the simulated seats were constructed by covering the frame of an automobile bucket seat with wire mesh and then with a layer of excelsior, followed with burlap. Figure 4.116 shows these three steps in the construction of the simulated seat. Thus, while this seat construction does not necessarily simulate the flame spread rates in an actual vehicle interior fire, it nevertheless provides a <u>difficult</u>, Class A (solid fuel) fire with both vertical and horizontal burning surfaces and with burning in depth as well as at the surface. The primary reason for selecting a seat configuration as the fuel bed was to provide a fire which the test subjects could relate to motor vehicles.

<u>4.6.1.3 Test procedures</u>: Since the major objectives of this test program were to determine the level of competence of the untrained test subjects, a test procedure whereby no one subject could view the test efforts of another subject was adopted for the pan fire tests. For these tests, the subjects were confined in a building adjacent to the pan test area which was outdoors. The extinguisher, in its standard mounting bracket, was attached to a table about 12 ft from the test pan. The extinguisher was weighed before and after each test to determine how much agent was used. The test fire was then ignited and allowed to burn 30 sec before commanding a subject to exit from the building to proceed with the extinguishment test. The time required for each participant to disengage the extinguisher from its

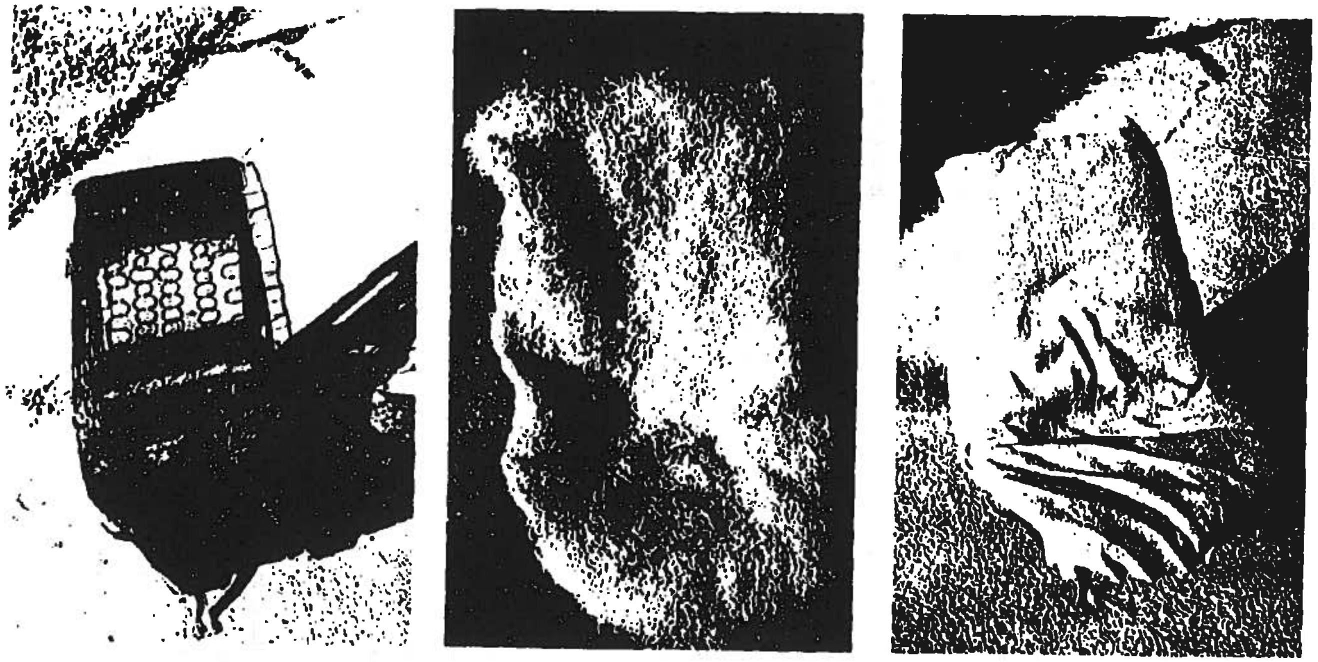


Figure 4.116. Construction of simulated seat for fire extinguishment tests.

mounting bracket and approach the fire, as well as the time required to extinguish the fire, or to discharge the contents of the extinguisher, was recorded. At the conclusion of each test, the subject was returned to another building so that he could not communicate with the remaining untested subjects. Each test was filmed for subsequent study and analysis. The test pan was then recharged, a fresh extinguisher was installed in the mounting bracket, and the same procedure was repeated for the next subject.

The only departure from this pan-fire test procedure occurred with about half of the younger men who were given some training (as will be explained in the next subsection) in the use of portable fire extinguishers; they were also permitted to watch the extinguishment efforts of each other.

None of the participants in the simulated seat fire tests received any indoctrination, nor were they permitted to observe any of the extinguishment tests. In these tests a small quantity of gasoline was sprayed over the surface of the seat to achieve rapid and uniform ignition. After a 30 sec pre-burn a subject was commanded to proceed with extinguishment, which again involved disengaging the extinguisher from the table, approaching the fire and attempting to extinguish it. As in the pan fire tests each extinguisher was weighed before and after the test to determine how much agent was applied to the fire.

<u>4.6.1.4 Test subjects</u>: The test subjects were chosen from four categories: males and females who were licensed drivers over 50 years of age and those who were under 30 years of age. It was assumed that the under 30 and over 50 age categories would bracket the capabilities of the driver population for extinguishing fires. The average age of the older women was about 57, and the older men about 64. The younger women and men averaged about 22.

None of the subjects exhibited any serious physical disabilities. Although most of the test subjects stated that they had seen similar fire extinguishers in schools or public buildings, none of the subjects had ever operated a fire extinguisher before nor had they paid more than cursory attention to the extinguishers and the operating instructions. These characteristics of the subjects were self-reported, and no additional effort was made to confirm their statements.

With the one exception in the case of younger men, no instructions were given to the subjects on the use of the selected dry chemical extinguisher other than the procedures for removing it from the mounting bracket and, in some cases, for operating the nozzle. The subjects were told that on command they were to remove the extinguisher from the mounting bracket (fastened to a table about 12 ft from the test fire), approach the fire and attempt to extinguish it. The only other instructions available to the untrained subjects were those printed on the extinguisher.

As mentioned previously, about half of the younger men were briefed in the operation of the extinguishers and the best techniques for extinguishing fires. These tests were run on two different days (November 18, 1971 and March 2, 1972) subsequent to completion of the rest of the program on October 30, 1971. This group of younger men was composed of engineers who were participating in a short course on safety at the University. Therefore, their technical background combined with the indoctrination on fire extinguishment made them (presumably) better prepared than the other half of the younger men who were chosen at random from the general population.

The instruction to these young engineers consisted of fire equipment manufacturer training films showing proper and improper techniques for attacking standard test fires as well as the movies which were taken on the previous attempts by uninstructed subjects to extinguish the test pan fire. The operation of the 2-1/2 lb dry chemical extinguisher was then explained to them, followed by a live demonstration by an experienced operator of its use on the test pan fire similar to the one they were to attempt to extinguish. They were encouraged to ask questions for which answers were supplied in detail, but they were not permitted to operate the extinguisher before the fire tests. The purpose of this indoctrination was to ascertain the value of verbal and visual training. A total of 139 subjects participated in the test program between September 10, 1971 and March 2, 1972: 87 on the pan fires and 52 on the seat fires.

4.6.1.5 Variables affecting capabilities of dry chemical extinguishers: Both the fire-fighting technique of the individual and the fire extinguishing mechanism of the agent determine the performance capabilities of a fire extinguisher, particularly in adverse weather conditions.

To compensate for these effects approval agencies, such as Underwriters Laboratories, have devised control fires for the rating of portable extinguishers. These control fires are fought by fully trained fire fighters under indoor (calm) conditions for the smaller, portable extinguishers. When larger fires have to be tested outdoors, the maximum allowable wind velocity is 10 mph. Higher wind velocities tend to give erratic results (an element of luck is involved) which compromises the extinguisher rating system. After the maximum size fire that can be consistently extinguished with a particular extinguisher by an experienced operator has been determined, a rating equal to 40 percent of that size in terms of area is given to the extinguisher. This reduction in the performance rating tends to compensate for a lower level of competence of the untrained user. Presumably the reduction in rating could also compensate, in some instances, for adverse weather conditions and longer pre-burn times than might be encountered in a real fire.

Dry chemicals extinguish fires by several mechanisms. The dry chemical agents act by forming a blanket over the fire which precludes oxygen, the solid particles just above the base of the fire significantly reduce the feedback of radiant energy to the fuel surface, decomposition of the solid and/or sublimation provide some cooling, and the solids or their pyrolysis products react chemically with the free radicals produced by the combustion reactions. In reality, for all dry chemicals, most of these mechanisms will be at work to varying degrees and for this reason dry chemicals tend to be more effective under windy conditions than other extinguishing agents are.

The techniques used to apply dry chemicals to a fire exert a profound effect on the time required to achieve extinguishment. Generally, the stream of dry chemical should be directed toward the base of the fire with a sweeping motion from side to side, so as to keep the fire in front of the dry chemical stream. Care must be exercised not to over-range the fire since it can flash back over the previously extinguished area.

On liquid fires, precautions must be taken not to "jet" the dry chemical stream into the liquid fuel since the resultant agitation and sloshing will enlarge the fire area. At the same time, if the dry chemical stream is directed only into the fire column, extinguishment will not be achieved. The objective, then, is to interpose a layer of powder between the liquid surface and the fire column which rests on the layer of vapors above the liquid surface.
On solid fires, such as the simulated seat fires, the best technique is to cover the flaming area quickly and uniformly

and then concentrate on reignitions as they occur by jetting the powder directly at the spot so as to penetrate the sublayers which are the real sources for reignition.

4.6.1.6 Weather conditions: Assuming that equivalent techniques are employed by experienced operators to fight the fire with a given dry chemical, it is generally easier to extinguish a fire in a gentle wind which tilts the flame away from the fuel bed than on a perfectly still and fair day when the flame is upright over the fuel bed. For a tilted flame the geometric view factor for feedback of radiation from the flame to the fuel bed decreases, and consequently the burning rate decreases. Furthermore, if the fire fighter approaches the fire from the upwind side, he can move closer to the base of the fire because the radiation to which he is exposed is also less for the tilted flame. From the closer range, the dry powder can penetrate the fire zone farther along its base, and in some cases, even blow off the fire. However, under higher winds, the dry chemical can be carried through the fire zone before all of the extinguishing mechanisms can be activated. Also, high winds tend to inhibit the lateral dispersion of the powder throughout the fire zone. These effects under high winds override any accompanying reduction in burning rate due to flame tilting with the net result of increasing the extinguishing times. To some extent, these deleterious effects can be overcome by nozzle design, particularly if the extinguisher is to be used exclusively outdoors.

All of the pan and seat fire extinguishment tests had to be run outdoors. To alleviate scheduling problems and to minimize the cost of paying subjects, once a test date was set, the tests were run regardless of the weather conditions. The tests were run on 14 different days extending over a period of 6 months. As a result, weather conditions ranged from a very calm day with light mist to high winds which gusted from variable directions at speeds exceeding 25 mph. On most of the test days the weather was generally fair with gentle winds rarely exceeding 10 mph, but on a few occasions light rain was encountered. Generally, only one age category, usually involving 5 to 15 subjects, was tested on a particular day. Except for the one day with strong, gusty winds, the results from the extinguishment attempts could not be related significantly to the prevailing weather conditions.

4.6.2 Results on Pan Fire Tests

As stated before, 87 subjects participated in the extinguishment trials on the gasoline pan fires; each subject performed only once. The distribution of participants by category was as follows:

Category	Number of Subjects	Test Dates
Younger Women (YW)	15	9/14/71
Older Women (OW)	3	9/18
	6	10/2
	5	10/30
Older Men (OM)	1	9/10
	6	10/9
	5	10/30
Younger Men (YM)	15	9/13
Young Engineers, Trained (YET)	15	11/18
Young Engineers, Trained (YET)	16	3/2/72

Overall, 32 extinguishments out of 87 attempts on the pan fires were achieved, or 37 percent. According to the U-L rating, 5:BC, the "average" person should be able to extinguish a liquid fire having an area of 5 ft^2 every time.

Only the older women on October 2, 1971, which was a very calm day with a light mist falling, had a perfect record 6 of 6. However, on two other days (September 18, light rain and wind and on October 30, moderately high winds), the older women failed on all eight attempts. On the other hand, 2 of 5 older men achieved extinguishment on October 30, 0 of 1 on September 10, and 1 of 6 on October 9 (all 3 days were fair with comparable moderate winds).

The young engineers who had received the prior indoctrination were successful 11 of 15 or 73 percent on November 18, 1971 whereas their counterparts of young men without indoctrination were successful 4 of 15 for 27 percent on September 13 under comparable weather conditions. It is tempting to conclude that this difference in performance, 73 versus 27 percent, can be credited to the indoctrination. However, on March 2, 1972, which was characterized by the strong, gusty winds, a group of young, indoctrinated engineers was successful in only 4 of 16 attempts or 25 percent, whereas on October 30 (moderate winds) 2 of 5 or 40 percent of the older men achieved extinguishment.

The younger women who performed on September 14 in moderate winds were successful in 4 of 15 attempts which matched the younger men without training on the previous day and under comparable weather conditions. For those trials which were successful, the total elapsed time between "grabbing" the extinguisher and extinguishing the pan fire varied from about 10 sec for the young trained engineers to about 20 sec for the younger women and the older women.

In summary, disregarding the weather conditions, the results are:

Category	Percent Success
Younger Women	27
Older Women	43
Older Men	25
Younger Men	27
Young Engineers, Trained	48

Thus, it would appear that the young engineers with indoctrination are not particularly more effective than older women except that their "reaction" time (10 sec) is half that of the older women. However, the difference in time between 10 and 20 sec for actual vehicle fires is not critical considering that the typical vehicle interior fire takes 3 to 4 min to build up to a serious level.

4.6.3 Results on Simulated Seat Fires

Fifty-two subjects had one trial each on the simulated seat fire tests as follows:

Category	Number of Participants	Date
Younger Women	15	9/21/71
Older Women	7	9/20
	5	9/27
Older Men	8	10/9
Younger Men	3	9/17
	14	9/23

Overall only 11 of 52, or 21 percent, of the seat fires were extinguished by all participants. None of the older men and only 1 of 15 younger women were successful. On September 27, 1971, in fair weather, 5 of 5 older women succeeded; whereas, on September 27 in rainy or misty weather, none of the older women extinguished the seat fire. The older women thus posted an average of 42 percent which is better than the younger men, 5 of 17 or

30 percent, achieved under more windy conditions coupled with a trace of rain on one day.

With respect to total elapsed time from "grabbing" the extinguisher to successful extinguishment, essentially no difference was found among the older women and younger women and men (the older men had no success). The time was approximately 20 sec.

4.6.4 Conclusions and Recommendations

Since the results of the extinguishment trials were not particularly conclusive, only some trends or intuitive opinions can be advanced:

1. With respect to the 5:BC rating, theoretically 100 percent of the participants should have extinguished the 5 ft^2 of gasoline fire as compared to the 37 percent that actually did. Even if one discounts the day in which the weather was particularly adverse (strong gusts on March 2, 1972) the percentage success increases to 40 percent. On this basis, the rating of 5 ft^2 is questionable.
2. The 5:BC extinguisher is probably adequate for handling the bulk of small upholstery or engine compartment fires in the early stages by completely inexperienced operators, but it could present a personal hazard to these same operators if they attempted to attack fires of the magnitude used in this test program.
3. Experience shows that training in fire extinguishment operations makes all the difference. However, in this test program the modest indoctrination given to 31 young engineers did not produce particularly gratifying results. In fact, based on these test results it would be speculative to conclude that young engineers with visual and verbal training can be relied upon to perform better than older women who have had no

indoctrination whatsoever. Even as modest as the indoctrination program was for these tests, the costs of administering and providing similar training to the entire driving population might outweigh the potential reduction in costs of property losses.

4. Requiring a small fire extinguisher as standard equipment on every vehicle would primarily be for reduction of property losses, but it is doubtful whether it would have a significant impact on vehicle fire fatalities.
5. Based on the results of this experimental test program, it is difficult to justify a requirement for a small fire extinguisher in every vehicle.

Taking all factors into consideration, it is recommended that until more conclusive experimental data are generated, carrying a fire extinguisher in a vehicle should continue to be a personal, voluntary option albeit good practice.

4.7 ANALYSIS OF MUNICIPAL RECORDS ON VEHICLE FIRES

The National Fire Protection Association reported that 461,000 automobile fires were attended or serviced by fire departments in 1970 (27). Since many automobile fires are not attended by fire departments, the total number of actual vehicle fires could be several times this figure. Regardless what the actual figure is, the 461,000 in itself represents a sufficiently high number to warrant some attention. Accordingly, the fire department records of four cities were surveyed to determine the primary causes and locations of motor vehicle fires and to determine if any patterns for their occurrence existed.

Approximately 3,000 motor vehicle fire run reports, primarily for passenger cars, were surveyed in Alexandria, Virginia; Tampa, Florida; and Norman and Oklahoma City, Oklahoma. Where possible the following information was recorded:

1. Manufacturer of motor vehicle
2. Year of manufacture (model year)
3. Date of fire
4. Location of fire
5. Cause of fire
6. Occurrence of injury or fatality
7. Approximate cost to repair damage.

It was not possible to glean all of the desired information from each motor vehicle fire run report because the reports were frequently incomplete.

The lack of sufficiently detailed information in the fire department run reports is not surprising. First, the firemen have the primary responsibility of extinguishing the fire as rapidly as possible. Their reports are very brief, listing only the minimum information required by their local administrative unit. The firemen themselves are generally not required to perform an investigation. Some investigations are conducted by fire marshals at a later date, but they are usually restricted to suspected arson cases.

The data presented in this section clearly show the inadequacy of fire run reports for analysis of the automobile fire problem. Although some insight can be gained with respect to the levels of uncertainty and inconsistency in existing reporting procedures, the records did not provide a sufficient base for a meaningful appraisal of the non-collision motor vehicle fire problem other than some general trends.

4.7.1 Automobile Fire Location and Cause

Figure 4.117 shows the location or cause of motor vehicle fires attended by the Oklahoma City Fire Department* during 1969 and 1970. One of the striking features of the results is the small percentage of fires attributable to collisions, about 2 percent. In fact, many of these so-called "collision fires" were not fires at all; the fire department was called to wash gasoline off the street following a collision. In practically all cases, these accidents occur within the city limits; they rarely involve injuries, much less fatalities. These findings support the conclusion (see Section 2.2) that the collision or post-crash fire, frequently involving injuries or fatalities, is essentially a rural phenomenon. This omission of the much more severe vehicle fire problem in rural areas should be kept in mind when

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*It is interesting to observe that of the 10,000 runs (including all service calls and false alarms) made by the Oklahoma City Fire Department during 1969, 1122 of them involved vehicle fires.

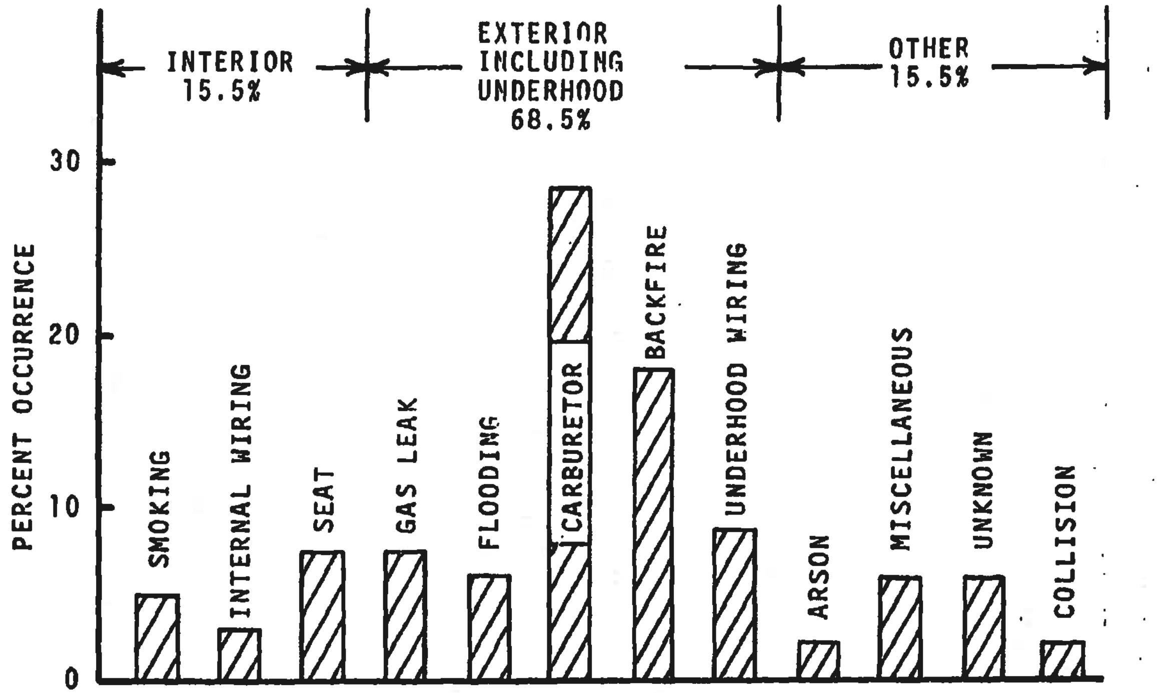

Figure 4.117. Location and/or cause of vehicle fires serviced by the Oklahoma City Fire Department in 1969 and 1970.

consulting the bulk of national statistics and NFPA data which for the most part are based entirely on urban experience.

According to Figure 4.127, about 60 percent of the vehicle fires attended by the Oklahoma City Fire Department involved the fuel system (gas leak, flooding, carburetor and backfire). As will be recalled from Section 2.2, fuel systems were also implicated in almost all of the <u>collision</u> fires in Oklahoma and Kansas. Consequently, corrective measures for the fuel system deserve the highest priority for reducing the incidence of all motor vehicle fires.

The fires that occur in the interiors of motor vehicles account for approximately 15.5 percent of the total fire runs to vehicle fires. Fire department records list interior wiring fires, seat fires, and smoking materials as principal causes. Although seat fires are identified separately, many of them might have been initiated by smoking materials.

Underhood wiring was given as the cause of fire in about 8.5 percent of the records surveyed for Oklahoma City. It was not possible to determine from the fire department run reports which particular electrical circuit was malfunctioning. However, fires that initiated in the underhood wiring frequently resulted in burning wiring other than that in which the fire started or igniting grease or oil on the engine. Spread of fire from the underhood wiring to the passenger compartment was infrequent, and the duration of underhood fires was generally short.

Conversations with fire marshals indicated that arson was a frequent, perhaps even the leading, cause of automobile fires. However, the run reports showed that only about 2 percent of the fires attended by the fire department could be classified as arson or suspicious. Further, it was found that the fire marshals seldom attended or investigated automobile fires unless there was strong evidence of arson or unless the fire resulted in almost total loss of the vehicle.

By the same token, firemen do not conduct investigations and therefore their reports would not routinely include a mention of arson. The above circumstances make the credibility of arson information suspect and inadequate for evaluation purposes.

4.7.2 Age of Automobiles Involved in Non-Crash Fires

As an automobile ages, both its mechanical components and its interior furnishings wear and deteriorate, becoming more susceptible to fire. Figure 4.118 shows the frequency of involvement and age of motor vehicles involved in non-crash fires in Tampa, Florida, during 1970. There were, of course, fewer 1971 models on the road during this period and the 1971 model data therefore cannot be compared directly with the remainder of the data. Since registration data by model year are also not available for Tampa, the following comments assume, of necessity, equal numbers of vehicles for each model year. As the motor vehicle age increased, the number of fires increased until the vehicles were about 5 years old. The number of fires for each model year then remained relatively constant for a few years before decreasing.

Qualitatively, the results suggest that as a motor vehicle ages, it is at least several times more likely to be involved in a non-crash fire than when it is new. The increased probability of fire begins when the vehicle is two or three years old and continues to increase for at least several years. Because the registration figures were not available for Tampa, it is not known whether the probability of fire reaches a plateau or not. The sharp decrease in the actual number of fires in older automobiles after they are about 10 years old is apparently due to the much higher scrap rate on old automobiles since the average age of vehicles over the past decade has stayed fairly constant around 5 to 6 years (28). Figure 4.118 also shows that any design change

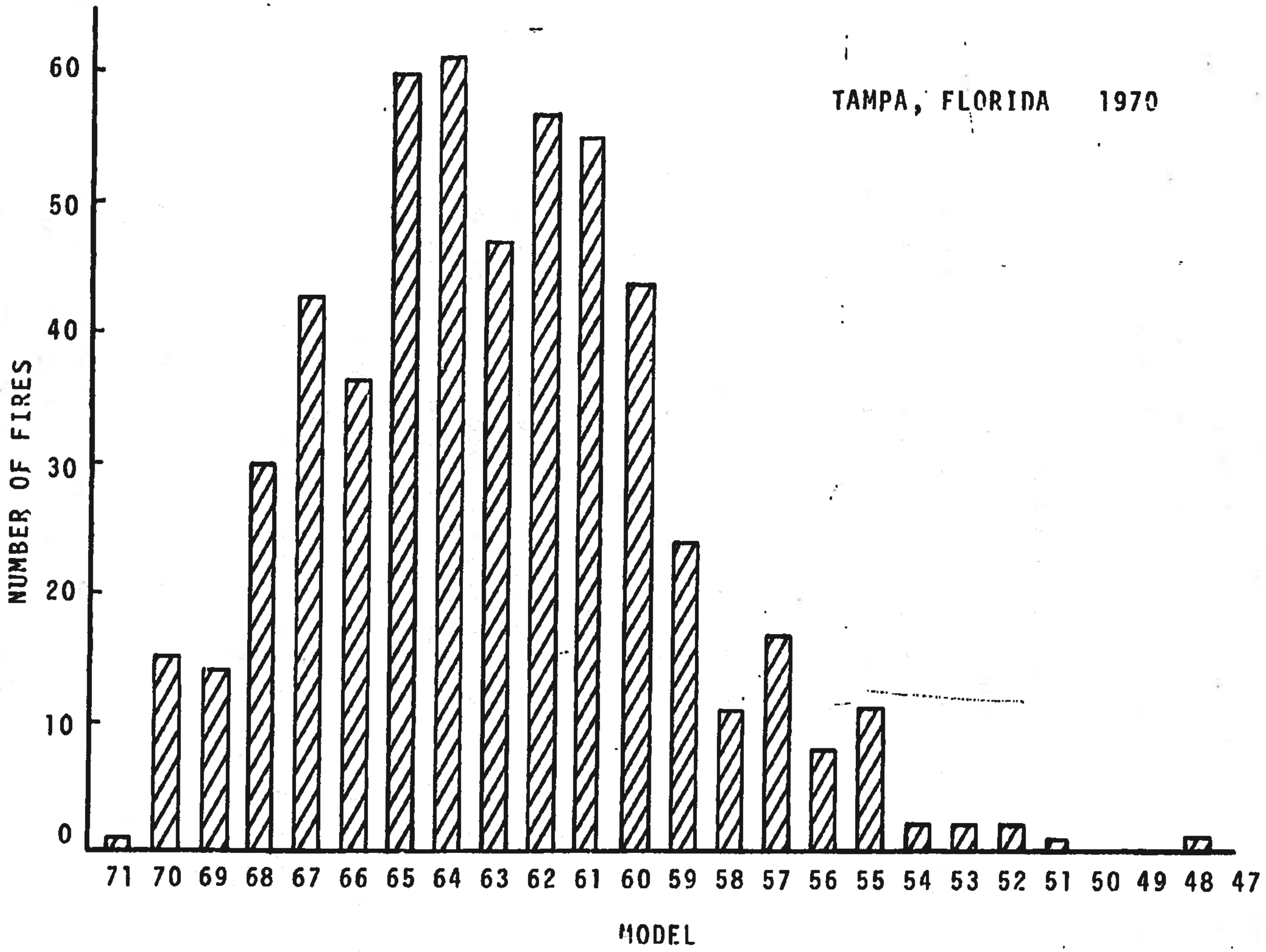

Figure 4.118. Frequency of non-crash fires by age of automobiles involved in Tampa, Florida.

or modification in the specifications for interior materials flammability cannot result in a significant reduction in the number of motor vehicle fires for at least several years after its introduction because the older vehicles are more likely to be involved in non-crash fires.

4.7.3 Occurrence of Non-Collision Automobile Fires by Month

Figure 4.119 shows the percent of the annual total motor vehicle fires reported by the fire department in Oklahoma City each month for 1968 and 1970. There is a small increase in the frequency of motor vehicle fires during the summer months. However this increase could be a result of increased driving or exposure during the summer.

4.7.4 Occurrence of Automobile Fires by Manufacturer

Although data on the occurrence of fires in vehicles according to the manufacturer were collected for the four cities in this survey, only Oklahoma City listed the make of the vehicle in almost every run report. (For example, Norman and Alexandria list "other or unknown" in more than 35 percent of the fires.) As shown by Figure 4.120, in Oklahoma City, approximately 56 percent of the motor vehicle fires occurred in General Motors vehicles, with 30 percent in Ford products, 5 percent in Chrysler products, and about 2 percent in American Motors vehicles. Since there were too few foreign vehicles to establish relative rankings they are all included under "other or unknown," as 7 percent of all motor vehicle fires.

It was not possible to obtain registration figures for any one city alone, so direct comparisons of the rate of fire involvement could not be established. However, registrations for the state of Oklahoma were available for new cars sold in 1969 and these data were used to estimate relative

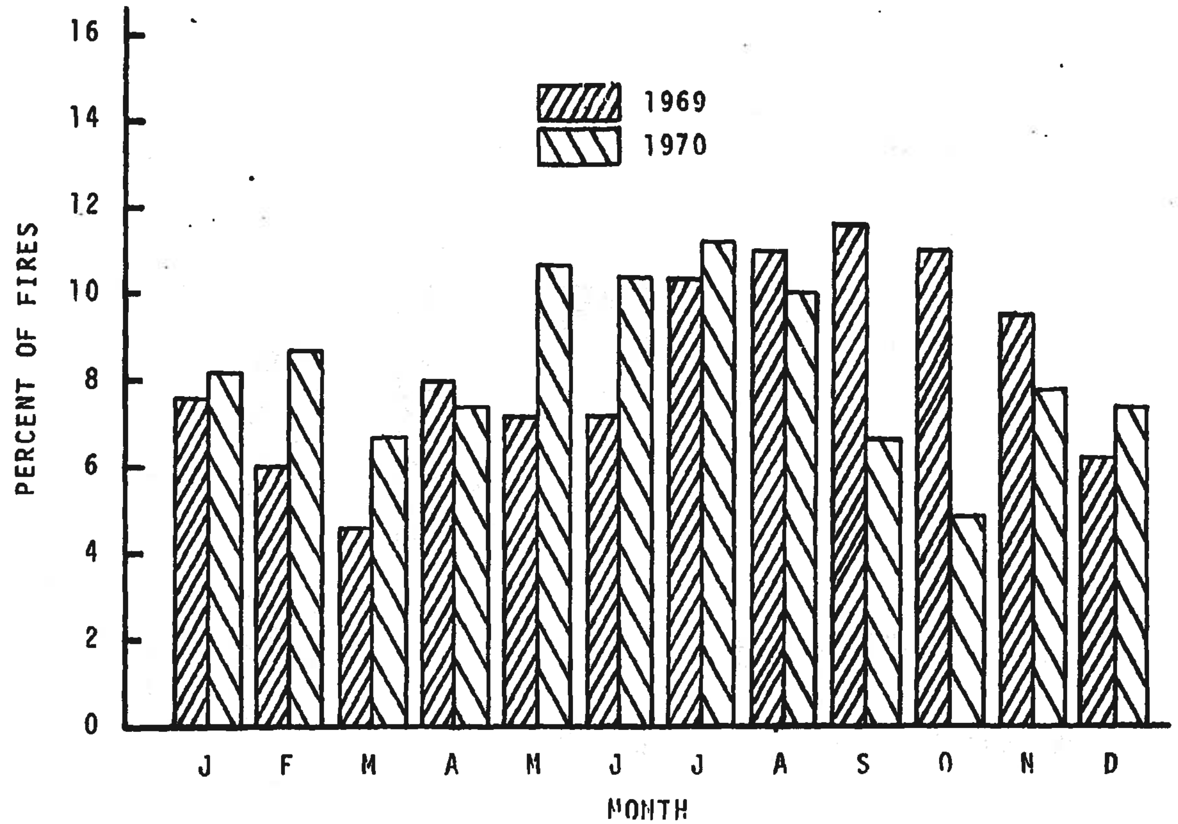

Figure 4.119. Distribution of motor vehicle fires by month in Oklahoma City for 1969 and 1970.

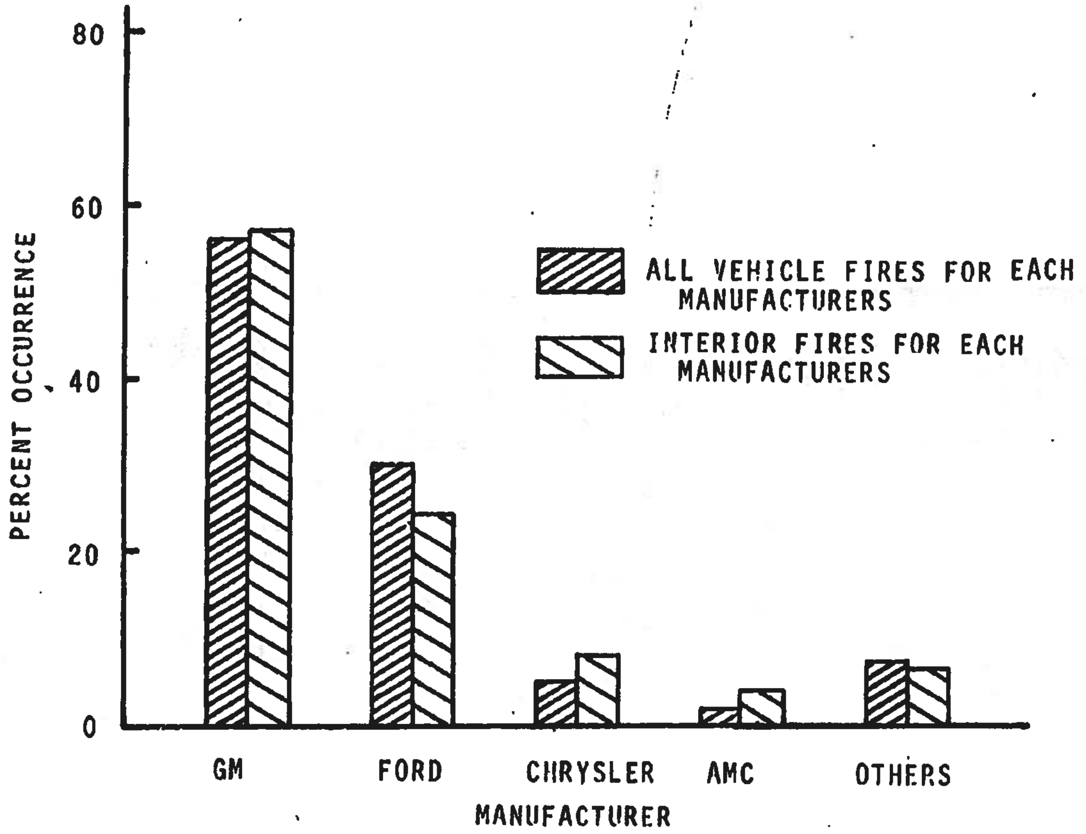

Figure 4.120. Distribution of non-crash vehicle fires by manufacturer, Oklahoma City Fire Department.

fire frequency for each manufacturer. The comparison was made only for Oklahoma City. Figure 4.121 shows the ratio of the percent occurrence to percent new car (1969) registration for each of the four United States manufacturers and for all foreign manufacturers combined. The rates are given both for all fires and for interior fires alone. The results show that General Motors products are involved in about 19 percent more fires than might be expected from their estimated numbers for all vehicle fires and a 21 percent greater involvement for interior fires alone. Ford products are involved in 22 percent more than might be expected for all fires, but about a normal proportion of interior fires. American Motors cars, while contributing less than would be expected for all fires, were involved in a 60 percent greater proportion of interior fires than would be expected from registration data on new vehicles. Because of the assumptions necessary to determine the relative numbers of different makes at risk, these rates developed from new car registrations for Oklahoma may not be representative of the study population in Oklahoma City.

4.7.5 Automobile Fire Costs

It is exceptionally difficult to determine the actual costs of motor vehicle fires from fire department records. For example, in a fire where a seat or carpet is burned, the damage may be listed as negligible, when it is quite apparent that the repair would amount to a complete replacement. Likewise, most damage due to underhood fires seems to have been underestimated. The most reliable damage estimates are those where the vehicle is a total loss; the average value can then be found from used car dealers or other listings.

The average loss from fires in which the damage was estimated by the fire department is given in Table 4.15.

The Tampa data are believed to be the most realistic because of their policy of checking with insurance companies

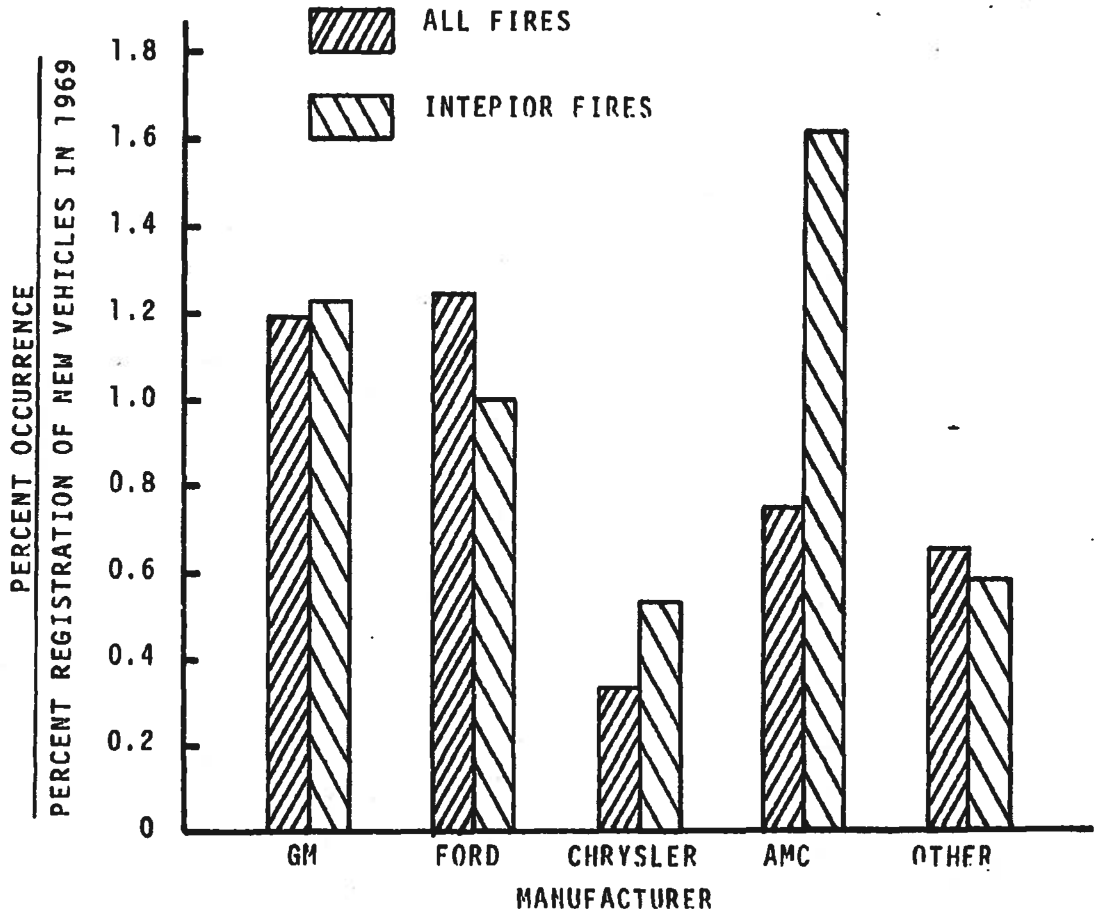

Figure 4.121. Relative occurrence of non-crash vehicle fires serviced by the Oklahoma City Fire Department in 1969 according to each manufacturer. (NOTE: Since registration of vehicles by manufacturer was not available for OKC, the state registration of new models sold in 1969 was used as the base.)

TABLE 4.15

AVERAGE COSTS OF AUTOMOBILE FIRES

Tampa, 1970	$250
Oklahoma City, 1970	170
Oklahoma City, 1969	140
Tulsa, 1970	160
NFPA, 1970 (27)	160

and vehicle owners in a sufficient number of cases in order to determine the true cost and to provide a guide for estimating loss in future fires. If the average cost of $250 per fire is applied to the 461,000 annual motor vehicle fires reported by NFPA, the direct cost would total more than $115,000,000 annually. This estimate is higher than the NFPA estimate of $73,800,000 (27). If the lowest average of $140, Table 4.15, is used, the direct cost would be over $64,000,000. None of these cost estimates, however, are representative of the total costs for all vehicle fires since the figure of 461,000 fires is based on the NFPA estimate which includes only those fires attended by a fire department.

4.7.6 Automobile Fire Injury

Estimates of fatalities incurred in motor vehicle crash fires have been discussed in the earlier report for Contract FH-11-7303 (4). Those fatalities occur primarily as the result of fuel spillage during a crash; the fuel-fed fire either ignites the interior materials of the vehicle or burns the passengers directly.

In non-crash fires injury is relatively rare, and even when injury occurs, it is usually minor. Of the more than 3000 motor vehicle fire run reports surveyed, 17, or less than 0.6 percent involved personal injury. Of those 17, 11 injuries were in fires involving collisions. Collision fires were approximately 2.0 percent of the total number attended, but injury occurred in nearly 15 percent of the collision fires. The records were inadequate to determine whether the injuries were due to impact or burns. Of the 3000 run reports for the 4 cities, only one fatality was recorded. It occurred as the result of an automobile-train collision in Tampa in which the fuel tank ruptured and the fire engulfed the entire automobile. Other non-crash fire deaths are known (from other information sources) to have occurred in the cities surveyed, but not in the years covered by this survey.

As was concluded in Section 2.2, death and injury from fire are clearly post-crash phenomena and occur infrequently in non-collision fires. Death and injury from motor vehicle fires are also predominantly rural phenomena.

4.7.7 Conclusions and Recommendations

The following conclusions are based on the data presented previously in this section:

1. Most non-crash motor vehicle fires involve the fuel systems, and fuel leaks at or near the carburetor are by far the most prevalent of these fuel-supported fires.
2. Non-crash motor vehicle fires seldom result in serious injury, and fatalities in non-crash fires are extremely rare; even minor injury is unusual.
3. The frequency of non-crash fires increases with the age of the vehicle up to 5 to 7 years. This increased frequency reflects deterioration or lack of maintenance. Beyond this point, the frequency of fire begins to decrease, reflecting the removal of vehicles older than 6 years.
4. There is evidence that more vehicle fires occur during the summer although fuel involved, non-collision fires stay essentially constant all year. The summer increases

are comparable to what might be expected from increased summer driving.

5. The direct cost of motor vehicle fire damage probably exceeds $115,000,000 annually.

These conclusions are based on a survey of fire department run reports. The quality of the run reports raises doubts concerning the validity of the results. However, the data are both reliable enough and detailed enough to support the conclusions, i.e., that the non-collision vehicle fire problem is primarily an economic loss problem, and that non-collision fires most frequently involve the fuel system. Based on the limited non-collision motor vehicle fire data available, the following recommendations are presented:

1. Since the fuel system is the primary cause in non-collision fires (also true in collision fires), it is recommended that the highest priority for reduction of property damage be placed on improved carburetor design and operation.
2. It is apparent that death and injury in motor vehicle fires are primarily post crash phenomena; therefore it is recommended that the efforts toward reduction of fire death and injury be placed on the integrity of fuel systems during and following a collision.
3. Considering the uncertainties inherent in the fire department run records, it is recommended that further refinements of the analyses of such information sources be abandoned since the effort would likely not be very productive.

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CHAPTER FIVE

RECAPITULATION

As an essential step in the development of techniques for objectively quantifying the performance of motor vehicle characteristics related to escape worthiness, a considerable body of data has been generated. Essentially the human and vehicle parameters which exhibit a demonstrable effect on relative ease of egress in an emergency situation have been identified and, in many instances, quantified. The most significant achievement during the current contract has been the development of several analytical models which establish the deterministic relationships among easily measurable escape parameters.

This chapter generalizes the principal findings in this program with cogent comments, to the extent possible, on the minimal performance limits that secure safe egress from vehicles in potentially hostile environments.

5.1 ANALYSIS OF INFORMATION

Perhaps the most vexatious aspect of this total contractural effort has been the lack of adequate statistical data for an evaluation of the nature and frequency of occurrence of impediments, inherent in the vehicle design characteristics, to the safe egress of occupants from a vehicle in an emergency situation. Even the raw data which constitutes the vehicle accident records or other information sources was found to be either too incomplete or too unreliable to support a preliminary statistical interpretation. In other words the body of available information lends itself to nothing more than vague inferences or tenuous presumptions relative to the relationship of conditional parameters to the general problem of escape worthiness.

The continuing examination of traffic accident reports and other official compilations under this contract was initially programmed as a modest effort to serve the purpose of expanding the available data base, rather than wholly as an end in itself. Nevertheless, the periodic requests from the offices of the National Highway Traffic Safety Administration for validation of fatality statistics, which were not encompassed by the contractural tasks, led to continuing--but sterile--attempts to extract the requested information from inadequate data sources.

5.1.1 Literature Review

Since the literature review, which consisted of surveying almost 10,000 published documents, recovered very little information useful to the total contractural purpose and effort, no extended analysis of these sources has been presented. Instead, the abbreviated discussions on the literature review have concentrated on the question of toxicity of combustion products and of the feasibility for establishing the frequency of, and making the distinction between, burn injuries and fatalities associated with vehicle fires. These two topics appear to be of current, overriding interest to the National Highway Traffic Safety Administration.

The nagging problem of the potential toxicity of the products of combustion from burning motor vehicle interior materials is far from resolution. The essential difficulty, beyond that of identifying candidate toxicants, is that there are still no adequate data on toxic levels for short-time exposures on the order of five minutes or less. The work done on aircraft interior fires by the Civil Aeromedical Institutes of the Federal Aviation Administration has produced results of a nature that makes the question more pressing than at the outset of these studies some three years ago. From their results it is possible to extrapolate to the conditions that might exist in an interior vehicle fire. Briefly, the burning of materials in a vehicle interior can produce dangerous concentrations of toxic products before the temperature rise in the interior becomes intolerable. One minute of burning of materials at the 4-inch per minute rate could produce dangerous levels of the toxicants. Since the expected temperature rise is of secondary concern compared to the toxicity, it is still imperative that an adequate determination of potential products and their toxic levels be made.

Attempts to find established sources of data on motor vehicle burn injuries and fatalities have been unproductive. Based on the limited data which are available, it appears that the ratio of fatalities to surviving burn injuries from vehicle fires is disproportionately higher than for any other types of fire. In other words, if a victim is burned in a vehicle fire, the probability is high that he will not survive.

5.1.2 Epidemiological Investigation

The efforts under this contract to expand the sample of collision fire data have been fairly effective, despite a reduction in the level of achievement expected, due to the failure of previously enlisted states to cooperate since they were unable to extract the desired information.

Based on limited studies in Illinois, California and New York within the last decade, one would conclude that about 2 percent of the vehicle fatalities are associated with post-crash fires. On the other hand, the investigation under this contract of vehicle fires in Oklahoma and Kansas, which is probably more comprehensive than previous studies, clearly shows a higher fatality rate associated with post-crash fires. During 1970 and 1971, 4.7 percent of the total non-pedestrian vehicle fatalities in Oklahoma were associated with burns in post-crash fires. The corresponding figure for Kansas over this same two-year period was 4.9 percent. However, these figures drop to 3.3 percent in Oklahoma and 2.5 percent in Kansas if only those fatalities which list burns as the principal or contributing cause of death on the death certificate are counted. This reduction in percentage seems excessive for the following reasons:

1. As discussed in Section 2.1, victims who are burned in vehicle fires usually die.
2. For every traffic fatality, forty crash victims escape with serious injury. Therefore (assuming the crashes are of equal severity), the odds are 40 to 1 that a fatality associated with a vehicle fire could have escaped with a serious injury in an identical crash situation except for fire.
3. A few death certificates were found in which no mention of burns was made, yet according to newspaper accounts, morticians or investigating officers, the victims were virtually incinerated.

General estimates indicate that the fatalities connected with vehicle submergences in water account for at least one, and probably two percent of the non-pedestrian traffic deaths. For the two-year period, 1970-71, 2.2 percent of the non-pedestrian traffic deaths in Oklahoma were associated with vehicle submergence. However, in more cases than not, the death certificate did not specifically list drowning as the cause of death; in fact, if only these cases are considered, the percentage of non-pedestrian traffic deaths due to drowning drops from 2.2 to 0.8 percent. This magnitude of reduction in the percentage is not borne out by the on-site investigations or analysis of the accident information. In the majority of cases the submerged vehicle is not damaged excessively nor are there any other indicators that the occupants could have sustained sufficient physical injuries to cause death. Therefore, it is believed that the "correct" percentage for drowning lies nearer the 2.2 percentage despite the fact that Oklahoma is probably below the national average on vehicle submergences.

The preliminary attempts to construct an epidemiological model of escape worthiness based on the on-site investigations of fire and submergence accidents show considerable promise. In fact, if such investigations were expanded to encompass all types of traffic accidents, then it is almost certain that the resulting epidemiological model will not only identify the critical escape worthiness parameters but will also rank them in order of importance.

5.2 ESCAPE WORTHINESS STUDIES

This phase of the research program concentrated on the experimental and analytical evaluations of the escape parameters and vehicle design features which could be related quantitatively to the emergency egress times necessary or available for survival in an adverse envelope.

5.2.1 Egress from Passenger Cars on Land

The principal factors governing the escape worthiness of passenger cars were identified under Contract FH-11-7303, and they were defined more perspicaciously in Section 3.1 of this report. The major accomplishment was the development of a predictive model for escape time which is based on a set of vehicle dimensions which can be easily measured. The predictive model takes into account a range of vehicle sizes from sub-compact through full size passenger cars, with a varying number of window and door exits, with and without injured passengers, and for both older and younger subject populations.

The predictive model is based on near-ideal escape conditions with regard to vehicle orientation and passenger shock and disorientation. The predicted escape times may be expected to increase if the vehicle is on its side or top, or if there is significant panic or disorientation of the passengers.

Predicted escape times across all conditions ranged from 7 sec to over 2 min. It seems unlikely that a problem could occur if an escape could be effected in 7-10 sec, while escape times greater than 2 min could definitely pose a problem of survival in a fire or water envelope. A "characteristic escape time" of approximately 30 sec might be viewed as the mean of the distribution of escape times, but it must be realized that the interaction of certain vehicles and subject groups produced escape times greater than 2 min. For example, in the case of older female passengers in a Volkswagen trying to assist an injured passenger through a window, the uninjured passengers never did succeed in removing the injured passenger.

In summary, data are now available to predict minimum escape times for a variety of vehicles under essentially ideal escape conditions. The interpretation of acceptable escape times under more realistic escape conditions will require considerably more experimentation as outlined in the multi-year research and development plan developed under Contract FH-11-7303.

5.2.2 Passenger Car Submergence Studies

A method for predicting vehicle floating times through the use of two relatively simple tests has been developed. These tests obtain the vehicle interior volume and the vehicle compartment air leak rate, which can then be correlated with water leak rate to predict vehicle floating time. The predictive model agrees with the results from a limited series of actual vehicle submergence tests conducted under Contract FH-11-7303.

A performance standard requiring a vehicle to float for 10 minutes after entering the water is probably adequate to allow passengers to make an escape. The required compartment sealing and other vehicle modifications to obtain such performance is not believed to be impossible to achieve or unreasonable, considering the additional benefits to be gained.

The other major thrust of the passenger car submergence studies has been the prediction of deceleration forces on the vehicle, vehicle sinking velocities and vehicle submergence attitudes upon entering a body of water with a given entry attitude and velocity. The analytical technique has been developed to the point where extensive model and full scale tests are needed for confirmation. Nevertheless, it is believed that the analytical predictions are quite representative. Of particular interest is the prediction that high deceleration forces occur at particular entry angles at high velocities. Such impacts could easily result in passenger injuries or shock, which reinforces the desirability of providing a longer floating time than presently occurs.

5.2.3 Bus Escape Studies

The studies on escape worthiness of buses have documented the escape times and related escape problems for school buses and intercity buses. The efficiency of different types of exits has been compared on school buses and intercity buses. Using the procedures outlined in Section 3.5, it is possible to estimate escape time for a variety of conditions. It is suggested that the maximum acceptable time limit for passengers to escape from a bus, using only half of the exits, should not exceed 90 sec.

A survey of existing intercity window escape exits demonstrated that hazards do exist in the form of sharp objects on the window frame which could be injurious to passengers attempting to exit through a window.

Although the new safety standard on Bus Window Retention and Release should enhance the escape worthiness of intercity buses, it needs to be more strict. Also, similar standards should be provided for school buses.

Finally, based on the strength data obtained for females and children, it is clear that in the design of emergency escape exits, more attention should be given to operating methods and force requirements as well as the interpretability of the accompanying operating instructions.

5.3 MOTOR VEHICLE FLAMMABILITY AND FIRE SAFETY

Like the escape worthiness studies, the assessment of flammability and fire safety was largely an experimental and analytical undertaking.

Several generalizations can be made regarding the vehicle fire problem. First, the greatest <u>number</u> of vehicle fires occur in the presence of an occupant. Second, the greatest <u>frequency</u> of vehicle fires is in no way directly involved with a collision. In this case occupants seldom suffer significant burns and fatalities are extremely rare. Property damage, however, can vary from minor to total. Third, collisions at low to moderate speeds in urban areas that result in fire often produce some burn injuries and to a lesser extent, fatalities. Fourth, the highway collision at high speeds is the most hazardous from the standpoint of fire-related injuries or deaths since both the exterior and interior of the vehicle can be engulfed in flames.

Under this contract, the scope was limited to fires in vehicle interiors and most of the effort was directed towards the assessment of flammability of the interior materials such as the upholstery, headliners, carpets and door panels. Although the quantitative magnitudes of the flammability parameters obtained during this study generally fell within the ranges studied under contract FH-11-7303, a much better understanding of the flammability mechanisms and criteria has evolved.

5.3.1 Ignition of Interior Materials

The materials used in current vehicle interiors are less susceptible to ignition than the human skin is to thermal damage at corresponding irradiance levels. Furthermore, as reviewed in Subsection 5.1.1, the thermal or temperature effect might be less serious than the potential toxic effect from combustion products. Thus, resistance to ignition is the most desired property from the standpoint of the flammability problem.

Measurements of ignition times at various levels of incident irradiance between 0.5 to 3 cal/cm^2-sec have been made on a variety of interior materials. These results can be described by a generalized correlating equation which provides reasonable estimates of the ignition time for any given irradiance level in the aforementioned range. A much better estimate of the ignition times can be obtained from the correlating equations for the individual classes of materials such as nylons, vinyls, sarans and cottons.

5.3.2 Burning Rates of Interior Materials

Unlike the ignition test which gives absolute values for ignitability, the burning rate test generates numbers which are grossly dependent upon the test apparatus and procedure. However, once a calibration factor for a particular material in a specified burning test has been established, then it is possible to predict the burning rate applicable to that particular test from a knowledge of the ignition characteristics and weight per unit area by means of the equations derived in Section 4.2. Since different burning rate test methods can give widely different burning rates for a given material, any prescribed burning rate limit is purely arbitrary and has basically little significance. On the other hand, a specified burning rate test is a useful instrument for comparing the flame spread rates of different materials. In this respect, the FMVSS 302 standard is just as good but probably no better than any other burning test.

As discovered previously under contract FH-11-7303 most vehicle interior materials can pass the 4 inches/minute limit according to the FMVSS 302 standard. However, this result does not justify reducing the acceptable burning rate limit since there is no evidence that the vehicle fire problem--such as it is--would be mitigated by such a reduction. As a matter of fact, the present "one-shot, pass-fail" criterion--irrespective of the prescribed magnitude of the acceptable burning rate limit--is somewhat risky. A more customary and conservative expression of the standard would establish a pass-fail criterion based on an authentic average burning rate of less than the prescribed limit with an average percent deviation from the mean of less than 10 percent in 10 or more repetitive burning rate tests. This modification in the performance standard would encourage more uniformity in the manufacture of vehicle interior materials. As it stands now, an element of luck is involved in passing the one-shot test, in which case there is no assurance that the burning rate of the next sample and all subsequent samples of the same material subjected to test would not show considerably higher burning rates.

Until more evidence becomes available, there is no justification for either raising or lowering the limit of 4 inches/minute. With the exception noted above--which involves a re-interpretation of the pass-fail criterion--the FMVSS 302 standard is reasonable.

5.3.3 Automobile Interior Fires

The purpose of these tests was to assess the potential life hazards, both thermal and toxic, of vehicle interior fires. These tests consisted in outfitting the "burn-car" with seats and headliners from a variety of makes of late model automobiles. Following ignition the temperatures, gas compositions, weight loss rates in the seats and smoke density were monitored throughout the test.

The carbon monoxide build-up, oxygen depletion and temperatures for the closed (no windows or doors open) vehicle gave no indication of reaching dangerous levels, except when latex or urethane foam mock-up seats were burned. Otherwise, the fire tended to die out without extensive damage to other than the seat. Although no toxic gases were detected by the colorimetric method of measurement, ample evidence of their presence was indicated by the test personnel who suffered severe respiratory reactions and headaches from exposure to the smoke.

If one door was left open, the fire became a raging inferno within 3 to 4 minutes after ignition, and within one minute after that, the entire interior was gutted. At this stage, the fire is virtually uncontrollable, and the temperature and burn hazard potentials are extreme. The catalyst for this sudden takeover appears to be the headliner which literally flashes and consequently involves the entire interior of the vehicle. Reducing the flammability of the headliner, even to the point of fabricating it from thin, perforated metal, would constitute a long step toward improving the flammability resistance of vehicle interiors.

During the flashover, the headliner is consumed at a rate of 150 to 200 inches per minute. The fact that the headliner passes the 4 inches/minute limit of the FMVSS 302 standard does not detract from the merit of the standard. As was shown in Section 4.3, the flashover rate can be predicted quite closely by correcting the FMVSS 302 horizontal burning rate for preheating, wind and burning widths. Similarly, the burning rates of the seats in both the closed and open door cases can be derived from the FMVSS 302 burning rate. Thus, these observations on the simulated interior fires exonerate the FMVSS test rather than negate it.

Finally, the observations on the simulated interior fires agree surprisingly well with the conclusions reached on investigations of "real-life" vehicle fires.

5.3.4 Fuel Modification

A review of the literature on the subject of gelled and emulsified fuels was essentially unproductive. The only claimed advance in the state of the art was the development of a gel with a lower viscosity that might ease the problems of moving it through the fuel system. The claim is also made that the gel is no more hazardous than ordinary gels despite its ability to drain from small openings at a faster rate.

While the fuel modification approach to increased fire safety still appears attractive, the effort to develop and use such fuels appears to be tapering off. If the potential incentive of the automobile fuel market could be harnessed to increase the effort, usable safety fuels could be developed.

5.3.5 Documentation of Fuel System Construction Practices

Since the majority of vehicle fires can be traced to a failure in the fuel delivery system, it is obvious that any improvement in the integrity of its design would have a salubrious effect. At the onset, it was hoped that sufficient information could be located and analyzed in order to develop the essential design criteria. After searching the literature and surveying the auto salvage yards, it was concluded that the only possible source of information on fuel system failures and specific problem areas might be the Multidisciplinary Accident Investigation Team reports. Unfortunately, their results are not as yet sufficient for these purposes. Consequently, the original objective of this effort had to be compromised.

A comparison of current (1972) fuel systems construction practice with that found by Fairchild-Hiller (1966-1968 models) was undertaken. It was concluded from this comparison that although automotive fuel systems may perform adequately to meet the requirements of FMVSS 301, they frequently fail to demonstrate cautious engineering design. Similarly, no extensive effort appears to have been made to attempt to prevent fuel penetration into the passenger compartment in some failure modes.

5.3.6 Fire Extinguisher Tests

In order to determine whether a significant proportion of the extinguishing capability of a small, hand-held extinguisher could be utilized by an untrained, representative sample of drivers, a series of fire extinguisher tests was run. Generally speaking the results were quite disappointing. As a matter of fact, a special group of young engineers, who were given verbal and visual indoctrination in fire extinguishment, were unable to achieve the performance implied by the extinguisher rating, although the engineers were moderately more successful than the untrained subjects.

On the basis of these test results, our intuitive recommendation under Contract FH-11-7303 that a fire extinguisher be required as standard equipment on all new vehicles is not defensible for fires of this severity.

5.3.7 Analysis of Municipal Records on Vehicle Fires

Probably the most significant finding from the survey of municipal fire department records is that burn injuries and fatalities from non-collision vehicle fires in urban areas are extremely rare. About 2/3 of these fires can be traced to small fuel leakage and only about 1/5 of these fires involve the interior of the passenger compartment. Older vehicles (beyond 5 to 6 years of age) have a higher frequency of fires, presumably due to deterioration of components or lack of maintenance. The principal identified causes of fires in the interior appear to be smoking materials and electrical shorts.

While the comments in the preceding paragraph are based upon a survey of fire department run reports, because of the uncertainties in the information on individual run reports, further analysis of such records is not recommended.

Non-collision fires constitute by far the highest percentage of vehicle fires of all types. Since these non-collision fires represent almost exclusively a property damage problem, it is possible to speculate what the cost effectiveness of a requirement to reduce flammability of vehicle interior materials would be. The property damage due to vehicle fires has been variously estimated at around $100 million per year. If 20 percent of this cost is due to interior fires, then the annual cost of vehicle interior fires is $20 million. Assuming 10 million new cars sold each year, the potential savings is $2.00 per new vehicle per year. This savings provides hardly any incentive since the cost of producing a non-inflammable interior would probably be quite substantial.

5.4 CLOSURE

In the course of this contractural effort a considerable amount of data relative to escape worthiness of vehicles and occupant survival was generated by application of traditional scientific methodologies. From these data, an attempt was made to prescribe objectively certain minimum levels of performance which would enhance the chances of occupant survival in or escape from a hostile envelope. However, what in fact constitutes an acceptable minimum level of performance cannot be resolved by further examination of scientific truths; rather the decisions must be reached by delicate subjective judgments of value in behalf of the population at risk. These issues that lie at the interface between science and any arbiter of "the social good" involve questions that can be stated in scientific terms but are in principle beyond the proficiency of science to answer. Such questions have been aptly labeled "trans-science" by Dr. Alvin M. Weinberg, Director of the Oak Ridge National Laboratory.

In some cases, the availability of abundant statistics on related past events serves as the measure of the demand for resolving the question. At the same time, statistics by themselves can be misleading, particularly if the impact of any decisions derived therefrom is not weighed against the consequences and other possible options. For example, the standard which imposes limits on vehicle emissions has aggravated the energy crisis by increasing the fuel consumption of new vehicles on the order of 25 percent. In the long run, the public could be affected more adversely by this corrective measure than if it had not been instituted in the first instance.

At the turn of the century when the population of this country was around 80 million, the annual deaths due to horse and buggy accidents was about 3700; thus, 0.005 percent of the population was involved annually. Today, the involvement of the population in vehicle deaths is on the order of 0.03 percent. Both of these percentages seem small, yet the difference between the two is a factor of 6. The question then becomes whether the cosietal benefits realized from greater population mobility outweigh the substantial increase in relative risk factor.

Next to vehicle accidents and falls, burns suffered in non-vehicle fires are the principal causes of accidental fatalities. Vehicles account for almost 50 percent, falls for 17 percent and non-vehicle fires for almost 7 percent. Drownings follow fires closely at around 6 percent, which leaves the remaining 20 percent of accidental deaths to all other causes. Approximately half of the fire deaths are attributed to flammable fabrics, half of which in turn are due to clothing. The question then arises: "What flammability limit on fabrics constitutes a rational, trans-scientific judgment?" Currently, the 4-inches/minute limit set by FMVSS 3C2 might appear unduly severe when viewed in the light that black rayon cloth, commonly used as a lining material in clothing, has a FMVSS 302 burning rate of 48 inches/minute; lightweight cotton burns at 7 inches/minute. On the other hand, the ordinary wooden kitchen match has an average burning rate of around 2.5 inches/minute, and the "paper" match burns even more slowly. It is quite obvious that arguments based on whether vehicle upholstery should be allowed to burn faster than a match or much slower than ordinary clothing materials leads nowhere.

Assessment of societal costs due to fires raises equally moot arguments. The property damage due to vehicle fires is frequently estimated at around $100 million annually.

If one adds to this figure the indirect costs associated with this damage, the total estimated losses are in the neighborhood of $400 million annually. Thus, vehicle fires are frequently regarded as a property-loss hazard. On the other hand, if 2000 fatalities per year can be associated with vehicle fires, then based on the Department of Labor's estimates which associate a $300,000 economic loss to each fatality, the cost of vehicle fire fatalities each year is in the neighborhood of $600 million. Surely, then, vehicle fires are not simply a matter of property loss.

The fact that statistics on vehicle accidents and fatalities can be troublesome to interpret is not only confined to the fire problem. For example, alcohol has been reported to be the greatest single underlying cause of vehicle fatalities. Other contributing causes, such as vehicles per square mile, population density, age of drivers, etc., are all reported to be factors which contribute to the vehicle death rate. Yet, the vehicle death rate in our states with the lowest alcohol consumption per capita combined with a most favorable position on the other factors (related to vehicle and population density, driving age, speed limits, etc.) runs considerably higher than in the states which have the highest per capita consumption of alcohol and simultaneously are plagued with more than their share of the other adverse factors. These statistics serve to emphasize that the underlying causes of vehicle fatalities have yet to be mastered because of the complex interplay of many parameters The elimination of one of these adverse parameters does not, of itself, guarantee a significant reduction in vehicle fatalities.

Thus, in attempting to protect the public at risk, all that one can hope for is the intuition to make the appropriate trans-scientific judgments as duly compromised in terms of the total societal impact. Although the name of the game, as indicated by the way it is being played, is "numbers", the answers lie in trans-scientific "wisdom" rather than scientific "austere truth."

CHAPTER SIX

NAMES, QUALIFICATIONS AND PARTICIPATION OF PRINCIPAL RESEARCHERS

TABLE 6.1

QUALIFICATIONS AND PARTICIPATION OF PRINCIPAL RESEARCHERS

Name	Highest Academic Degree	Experience	Participation in Contract FH-11-7512				Responsibility
			Primary Area				
			Information Analysis	Epidemiology	Escape Worthiness	Flammability	
C. M. Sliepcevich	Ph.D. Chem Engr	27 yrs as professor & consultant	X	X	X	X	Program Manager
W. D. Steen	Ph.D. Preventive Medicine	9 yrs as professor & 12 yrs in Pub. Health		X			Principal Investigator
J. L. Purswell	Ph.D. Ind Engr	4 yrs industry, 5 yrs as prof. & consultant			X		Principal Investigator
R. F. Krenek	Ph.D. Ind Engr	4 yrs industry 2 yrs as prof.			X		Principal Investigator
J. R. Welker	Ph.D. Chem Engr	7 yrs in fire research				X	Principal Investigator
T. D. Peace	M.S. Environ. Health	5 yrs in gov't 2 yrs in accident research		X			Research Associate
R. E. Cullen	M.S. Mech Engr	20 yrs research and teaching			X		Research Associate
J. N. Ice	B.A. English	6 yrs in gov't 3 yrs in industry	X	X	X	X	Project Coordinator
R. G. Rein, Jr.	Ph.D. Engr	5 yrs in fire research				X	Research Associate

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