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Firewall Design in Buses To Mitigate the Propagation of Engine Fires

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16. Abstract

This report describes the results of research that was conducted to evaluate designs of the partition between the engine compartment and the passenger compartment in motorcoaches (rear-mounted engines), medium-size buses (forward-mounted engines), and school buses. The research examined the following.

- The ability of the partitions to mitigate the propagation of fire originating in the engine compartment into the passenger compartment.
- An accounting of openings or gaps in partition designs that could allow fires to propagate and noxious gases to flow into the passenger compartment.
- Conformity of firewall designs to identify benchmarks in terms of their ability to mitigate propagation of engine fires into passenger compartments.
- Practical considerations and design constraints for improved partitions to mitigate propagation of engine compartment fires into the passenger compartments.

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Table of Contents

List of Figures

List of Tables

Executive summary

The research described in this report was conducted due to NHTSA's safety concerns related to engine fires in buses. Three tasks were carried out, as follows.

- Task 1: Performed a review of national and international industry standards, best practices, and regulations for the design, development, and testing of partitions between the engine and passenger compartments to mitigate propagation of engine compartment fires in light passenger vehicles, buses, and medium-duty trucks.
- Task 2: Documented the engine compartment partition designs for selected motorcoaches, medium-size buses, and school buses and at a minimum, including the following items in the documentation for each design:
    - The size and location of any openings in the partition; and
    - Materials used for cables or ducting or other items associated with each opening.
- Task 3: Identified firewall design benchmarks and performed an engineering assessment of the documented partition designs against these benchmarks. Evaluations were performed on firewalls in motorcoach models, medium-size bus models, and school bus models. The evaluations were supplemented with an analysis to identify potential improvements to the partition design and assess the feasibility of their implementation.

During the course of the project, the following key observations were made.

Task 1: Literature Review

- The majority of the studies reviewed focus on passenger vehicles and may not be entirely relevant for buses.
- Experience of fire suppression system effectiveness against bus engine compartment fires is inconclusive. A conference paper presented in 2010 mentions that Sweden had 6 or 7 complete bus burnouts per year prior to 2004, when insurance companies started requesting that approved fire suppression systems be installed in the engine compartments and had none since. In 2018 a more recent conference paper reported that fire statistics in Israel do not show any evidence of an effect, 3 years after publication of a new standard requiring fire detection and suppression systems in the engine compartment of buses.
- A study conducted at the National Institute of Standards and Technology (NIST)[1] (Hamins, 1998) shows that simply applying an intumescent coating[2] to the fire-exposed surface can be effective in significantly reducing and delaying conduction heat transfer, but has little or no effect on preventing the propagation of an engine fire into the passenger compartment through openings in the firewall.
- The occupant evacuation times recorded in the four studies reviewed in this project are very low. However, they do not account for the delays in detecting the fire and making

[1] Gaithersburg, MD.

[2] An intumescent paint coating reacts to heat by swelling in a controlled manner to many times its original thickness, producing a carbon char formed by many small bubbles that act as an insulating layer to protect the substrate.

the decision to respond, the time to bring the bus to a stop, complications if the bus is involved in a collision, etc., which can significantly delay evacuation as shown in a school bus evacuation exercise in Lee's Summit, Missouri, in 2018 (Schlosser, 2018). The minimum fire resistance rating of 15 minutes specified in the U.S. Federal Transit Administration's (FTA) recommended fire safety practices has a safety margin that should be more than sufficient to account for the extra time. Moreover, fire departments generally respond within 15 minutes.

Task 2: Firewall Documentation

- Six different sites were visited and 16 buses (model years from 1994 to 2021) were examined, as follows.
  - 3 motorcoaches, all with rear-mounted engines
  - 2 transit buses, both with rear-mounted engines (one hybrid)
  - 5 medium-size buses, all with forward-mounted engines
  - 6 school buses (3 full-length, 1 reduced length and 2 medium-size), all with forward-mounted engines
- For each bus surveyed, several summary statistics are reported. These include the total estimated firewall area, the total penetration area (sum of the areas of all penetrations in the firewall of a given bus), the total penetration fraction (ratio of total penetration area and firewall area), total number of penetrations, and the average area per penetration.
- The firewall area varied between from 695 to 7,648 in^2, the total penetration fraction varied from 0.9 to 11.8 percent and total number of penetrations varied from 1 to 62.
- Summary observations for Task 2 included the following.
  - Rear-mounted transit buses and motorcoaches have the fewest visible penetrations and lowest total penetration fraction.
  - Full-length school buses (forward-mounted engines) have the highest number of visible firewall penetrations and highest total penetration fraction.
  - Medium-size buses have nearly the same total penetration fraction as full-length school buses with one-third of the number of penetrations.

Task 3: Engineering Assessment

- Engine fires are much less likely to spread to the passenger compartments in buses with rear-mounted engines (motorcoaches and transit buses) compared to buses with forward-mounted engines (school buses and medium-size buses) because firewalls in buses with rear-mounted engines are not in direct contact with the passenger compartments and have far fewer penetrations with much smaller total penetrated area. Furthermore, buses with a rear-mounted engine were found to have much better benchmark ratings than buses with forward-mounted engines.
- The proximity of a forward-mounted engine to the driver and the principal vehicle exit raises the importance of the firewall's ability to mitigate fire spread from the engine to the passenger compartment in school and medium-size buses. Firewall design features that mitigate the spread of flames and gases have been identified as follows.
  - Improve the thermal resistance of the firewall by covering the engine side with an intumescent coating.

    - Periodically inspect the cowling and perform repairs as needed, or replace deficient or inadequate cowling with a fire-resistant design (inspections and repairs are relatively easy to do in existing buses, but replacement is much more complicated).
    - Penetrating items such as electrical cables and tubing routed through a pipe flange that is screwed to the sheet metal of the firewall as shown in Figure 17(b), instead of through an unprotected opening in the firewall with a grommet as shown in Figure 17(a). Annular space around the penetrating items filled with fire-resistant sealant.
    - Heating, ventilation and air conditioning (HVAC) system components and ductwork made with thermally insulated metal components (in lieu of plastic parts); fire damper installed to prevent toxic smoke from flowing into the passenger compartment.
- Defense-in-depth and compensatory measures are identified that have the potential to enhance fire safety. Examples are the implementation of frequent and rigorous preventative engine inspection, maintenance and repair programs and development of updated instructional materials to facilitate safe egress in the event of a bus fire.

Introduction

The National Highway Traffic Safety Administration awarded a contract to Southwest Research Institute (SwRI) to conduct research to evaluate designs of the partition between the engine compartment and the passenger compartment, in this report and commonly referred to as the "firewall," in motorcoaches with rear-mounted engines, and school buses and medium-size buses with forward-mounted engines. The research examined:

- The ability of the partition to mitigate the propagation of fire originating in the engine compartment into the passenger compartment.
- The effect of openings or gaps in partition designs on its ability to mitigating fire propagation.
- Potential improvements of current partition designs for mitigating propagation of engine fires into the passenger compartment.
- Practical considerations and design constraints for implementing these improvements in retrofitting existing buses and in the development of better-performing designs for newly constructed buses.

The work was performed from August 28, 2020, to November 29, 2021.

Background

There is on average about one school bus and one motorcoach fire daily in the United States (Meltzer et al. 2016). About 35 percent of motorcoach fires originate in the engine compartment and subsequently spread into the passenger compartment (Meltzer et al. 2016). While the Federal Motor Vehicle Safety Standards (FMVSS) do not set minimum performance requirements regarding flammability of materials in the engine compartment and the fire resistance of firewalls in motor vehicles in the United States, the National Fire Protection Association (NFPA) 556 (National Fire Protection Association, 2020b) has published guidance on mitigating fire hazard to motor vehicle occupants. NFPA 556 provides strategies to mitigate the effect of fires originating in the engine compartment, including the following.

- Decreasing the ignition propensity of materials in the engine compartment and ductwork.
- Decreasing the heat release of materials in the engine compartment and ductwork.
- Separating engine compartment from the passenger compartment by a barrier that inhibits or prevents the passage of flame and hot gases.
- Improving bus emergency egress designs to allow adequate time for bus occupants to evacuate the bus in the event of a fire.

However, NFPA 556 does not provide further specifications to comply with the strategies outlined above to allow for design flexibility.

The Economic Commission for Europe (ECE) R.107 (United Nations Economic Council for Europe, 2014) requires that buses in the European Union be designed with partitions made of heat-resistant material between the engine compartments and the rest of the vehicles. Additionally, warning systems to the drivers are required for buses with the engine compartments in the rear of the vehicles in the event of excess temperature in the engine compartments. However, ECE R.107 does not specify the properties of the partition that would provide adequate heat resistance.

According to the NFPA's report on vehicle fire trends and patterns, annual deaths and injuries from vehicle fires have dropped by approximately 60 percent between 1980 and 2011 (Ahrens, 2020). It is encouraging that fire frequency has been steadily diminishing. However, the frequency of bus fires remains high resulting in economic loss, though they do not result in injury or fatalities to bus occupants. NHTSA developed test procedures (Huczek & Blais, 2015) for evaluating fire detection and suppression systems in motorcoaches in 2015. The research resulted in demonstrated test procedures for fires originating in the engine compartment that were specific to the particular bus designs under study, but these were not comprehensive enough for inclusion in the Federal motor vehicle safety standards.

Several studies conducted under the March 7, 1995, Settlement Agreement between GM and the U.S. DOT, provide data characterizing passenger vehicle fires and methods to evaluate fire performance of components and materials used in vehicle construction.[3] [4] The citation in the

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[3] Motor Vehicle Fire Research Institute, Charlottesville, VA, /www.mvfri.org/Library/library.htm This organization went out of business about 2017 but was superseded by the Automotive Safety Research Institute, which maintains the MVFRI website and its records and links.

[4] Links to the individual reports are including with the citations in the reference section.

footnote is provided instead of the NHTSA docket, because the relevant publications are organized and more readily accessible at the Motor Vehicle Fire Research Institute (MVFRI) site. This large database of tests and reports could provide valuable information on strategies to mitigate the propagation of engine compartment fires.

Finally, a review was made of the report from an NTSB investigation of a school bus fire in Oakland, Iowa (National Transportation Safety Board, 2019b), as well as subsequent NTSB recommendations (National Transportation Safety Board, 2019a), along with a web search for magazine and website articles on this and other school bus fires that originated in engine compartments.

Objectives of the research

The research described in this report was conducted as follows.

- Performing a review of national and international industry standards, best practices and regulations for the design, development, and testing of partitions between the engine and passenger compartments to mitigate propagation of engine compartment fires in light passenger vehicles, buses, and medium-duty trucks.
- Documenting the engine compartment partition designs for selected motorcoaches, medium-size buses, and school buses and at a minimum, including the following items in the documentation for each design.
    - The size and location of any openings in the partition.
    - Materials used for cables, ducting, and other items associated with each opening
- Performing an engineering assessment of the documented partition designs on at least three motorcoach models, three medium-size bus models, and three school bus models, and supplementing the assessment with
    - An analysis to identify potential improvements to the partition design and assess the feasibility of their implementation; and
    - An evaluation of the partition's ability to mitigate propagation of engine compartment fires into the passenger compartment.

Methodology

The research consisted of three tasks that are briefly described in the following sub-sections.

Task 1: Literature review

A literature search was conducted to identify research projects, tests reports, case studies, incident data analyses and related documents that provide insights into the different factors that contribute to the propagation of an engine fire into the passenger compartment of a motor vehicle. Some of these publications that were reviewed explore various strategies for preventing, delaying, or minimizing the likelihood of fire spread that leads to injuries or fatalities of occupants in the passenger compartment. The literature review involved four sets of documents.

Standards, practices, and regulatory requirements

Two important standards were mentioned in the request for proposal (RFP).

- *NFPA 556: Methods for Evaluating Fire Hazard to Occupants of Passenger Road Vehicles, 2020 Edition*, National Fire Protection Association (National Fire Protection Association, 2020b)
- *Regulation No 107 of the Economic Commission for Europe of the United Nations (UNECE)—Uniform provisions concerning the approval of category M2 or M3 vehicles with regard to their general construction* (United Nations Economic Council for Europe, 2014)

As a possible design improvement of barriers between the engine and passenger compartment, NFPA 556 proposes using a barrier that prevents passage of flame and hot gases when tested in a furnace according the ASTM E119 fire resistance standard. ASTM E119 is used primarily to determine the fire resistance rating of structural elements and assemblies in building. A wall, for example, is exposed to the standard fire, which is characterized by the gas temperature-time curve in the furnace, for a specified duration or until one of the failure criteria is exceeded. The primary failure criteria are based on the temperature of the unexposed surface of the wall reaching the ignition temperature of flammable solid combustibles or the passage of flames or hot gases through small openings in the test specimen. The following furnace test standards use the ASTM E119 standard fire exposure to qualify thermal barriers for foam plastic insulation and fire stopping of through-penetrations.

- *NFPA 275: Standard Method of Fire Tests for the Evaluation of Thermal Barriers, 2017 Edition*, National Fire Protection Association
- *ASTM E814-13: Standard Test Method for Fire Tests of Penetration Firestop Systems*, ASTM International

These standards could serve as the basis for a fire test method to evaluate firewalls.

Finally, based on a search for pertinent standards, practices and regulations, the following were added to the list of documents to be reviewed.

- "United Nations Regulation ECE 36—Uniform provisions concerning the approval of: large passenger vehicles with regard to their general construction" (United Nations, 2008)
- *Regulation No 118 of the Economic Commission for Europe of the United Nations (UNECE)—Uniform technical prescription concerning the burning behavior and/or the capability to repel fuel or lubricant of materials used in the construction of certain categories of motor vehicles* (United Nations Economic Council for Europe, 2020)
- *National School Transportation Specifications and Procedures (NSTSP), 2015 Revised Edition*, adopted at the 16th National Congress on School Transportation (NCST) (National Congress on School Transportation, 2015).
- *Emergency and Rescue Procedures: A Guideline Manual for School Bus Involvement* published in 2004 by the National Association of State Directors of Pupil Transportation Services (NASDPTS) (Tull et al., 2004).
- *Recommended Fire Safety Practices for Transit Bus and Van Material Selection*, published in the Federal Register by the U.S. Federal Transit Administration (FTA) (58 C.F.R. § 201, 1993).
- *Standard Bus Procurement Guidelines* published in 2021 by the American Public Transportation Association. Settlement agreement between General Motors Corporation and the U.S. DOT

The 1995 settlement agreement between GM and the U.S. DOT resulted in a large volume of research on the subject of motor vehicle fires. However, only part of this work and the reports are relevant to the present study. To identify these reports, a search was performed for the words “bulkhead,” “firewall,” and “separation.” The reports with matches were inspected to verify that the contents were indeed relevant to the present study. Ultimately, the list of reports was narrowed down to 38, which were grouped in the following categories.

- Case studies and investigations
- Vehicle accident data analyses
- Full-scale post-crash motor vehicle engine fire tests
- Initiation and severity of engine fires
    - Initiation due to an electrical fault
    - Ignitability of fluids
    - Flammability of polymeric materials
    - Heat release rate of HVAC modules
    - Use of FR-treated materials
    - Fire suppression systems

- Fire propagation through the firewall
    - Thermal properties of firewall materials
    - Propagation through ducts and openings
    - Use of intumescent coatings
    - Mathematical modeling

Open literature search

A survey of the open literature was conducted to identify additional publications pertinent to the present study. About a dozen papers were found in several of the aforementioned categories and in the new category of forensic analysis.

Investigative reports and articles on school bus fires

A review the report of an NTSB investigation of a school bus fire in Oakland, Iowa (Meltzer et al. 2016), is made, along with a web search for magazine and website articles on this and other school bus fires that originated in engine compartments.

Task 2: Documentation of selected firewall designs for different types of buses

The second task involved documenting the engine compartment partition designs for selected motorcoaches, medium-size buses, and school buses. The resulting documentation included photographs, LiDAR scans, measurements of the size and location of openings in the partition, cataloging materials used for cables or ducting or other items associated with each opening, etc.

The initial approach involved desk reviews of drawings supplied by motorcoach vendors. However, the drawings were very intricate, which made finding the desired information challenging. It was therefore decided to focus on obtaining the information via site visits. Table 1 provides a list of the sites that were visited and buses for which the firewalls were documented.

Table 1. List of Visited Sites and Buses for Which the Firewalls Were Documented

Date	Site	Buses for which the firewalls were documented
May 11, 2021	NHTSA Vehicle Research and Test Center (VRTC) East Liberty, Ohio	1994 MCI 102-DL3 motorcoach 2004 long IC school bus (School Bus Body #969164) 2006 short IC school bus (Model BE200)
May 13, 2021	Applus+ IDIADA Adelanto, California	2014 Starcraft Prodigy bus, GM engine 2016 Microbird MB-11school bus, Ford engine 2016 Van-Con Type B wheelchair bus, GM engine 2017 Lion 360 school bus, Body No. 11498
July 1, 2021	Navistar/IC Bus San Antonio, Texas	2008 IC Maxxforce DT3200 4×2 commercial bus 2021 IC full-length school bus (Model CE Series)
July 8, 2021	Greyhound Lines Dallas Maintenance Center Dallas, Texas	2009 Prevost X3-45 motorcoach, Detroit engine* 2009 Prevost X3-45 motorcoach, engine removed* 2013 MCI D4505 motorcoach, Cummins ISX engine

Date	Site	Buses for which the firewalls were documented
		2013 MCI D4505 motorcoach, engine removed* 2014 Prevost X3-45 motorcoach, Volvo engine* 2019 Prevost X3-45 motorcoach, Volvo engine
July 9, 2021	First Transit Brownsville Service Center Brownsville, Texas	2008 Champion medium-size bus, GM engine 2009 Gillig 35-ft. transit bus, Model G2 2020 Gillig hybrid (diesel-electric) 35-ft. transit bus,
July 15, 2021	FirstGroup Tampa, Florida	2021 Ford Cutaway (Forest River, Inc.) para-transit van 2021 Ford E-450 Cutaway (Starcraft) para-transit bus

*Inspections of buses marked with * were limited in scope and were performed with the purpose of obtaining additional documentation of specific features of the firewall designs (for example, it is easier to observe firewall penetrations when the engine has been removed).*

The 16 buses that were examined were constructed between 1994 and 2021 and consisted of:

- 3 motorcoaches, all with rear-mounted engines,
- 2 transit buses, both with rear-mounted engines (one hybrid),
- 5 medium-size buses, all with forward-mounted engines, and
- 6 school buses (3 full-length, 1 reduced length and 2 medium-size), all with forward-mounted engines.

Task 3: Engineering evaluation of the documented firewall designs

In Task 3 a detailed engineering assessment was made of the partition designs documented in Task 2. The methodology for conducting this evaluation involved the following steps.

- Define a firewall design that can serve as a benchmark for the different types of buses and/or engine configurations (rear vs, front mounted) that were documented in Task 2.
- Evaluate the documented firewalls from the site visits using the following approach.
    - Rate the firewall against the benchmark for the four mechanisms identified in NFPA 556 by which engine fires can affect the health and safety of people in the passenger compartment.
    - Determine how the firewall design can be improved to meet the benchmark specifications.
    - Assess the practicality of the improvements and identify constraints for implementation in existing and new buses.
- Perform an engineering assessment of the effect of a collision on each firewall design’s ability to mitigate fire propagation.

- Identify potential defense-in-depth measures (added layers of fire protection) and/or compensatory measures (to offset deficiencies in firewall performance) to reduce the risk for fatalities and injuries due to an engine fire.

The four mechanisms for the transfer of heat, flame, or hot gases from the engine to the passenger compartment identified in NFPA 556 are:

- Heat conduction through the firewall;
- Flow of hot and toxic gases and flame propagation through ductwork. A distinction is hereby made between noncombustible and combustible ductwork. For the former a fire-rated damper could be used to prevent toxic gas and flame propagation. A damper is not likely to be effective for the latter because the ductwork is subject to burn-through;
- Flow of hot and toxic gases and flame propagation via openings around penetrations through the firewall; and
- Flow of hot and toxic gases and flame propagation through openings in the firewall created by a collision.

Task 1: Literature review

This section provides the results of a literature review that was conducted to meet requirement C.5.3 in the solicitation. The review consists of three parts. The first part covers applicable guidelines, standards, and regulations. The second part focuses on pertinent research studies. The section concludes with a discussion of some pertinent parts of an NTSB report of a 2018 Oakland, Iowa, school bus fire and of a collection of magazine articles on this and other school bus fires that started in the engine compartment.

The purpose of the firewall is to prevent or delay propagation of flames and hot gases from an engine fire into the passenger compartment, and thus avoid or minimize the likelihood of injuries or fatalities of occupants due to exposure to heat and toxic products of combustion. However, the hazard to the passengers is also affected by the severity of the engine fire and the time for safe evacuation. The scope of the literature review therefore was expanded to include these factors.

Applicable guidelines, standards and regulations

The two documents in this category that were mentioned in the solicitation, NFPA 556 (National Fire Protection Association, 2020b) and UNECE Regulation No. 107 (United Nations Economic Council for Europe, 2014) (together with some related UNECE regulations, United Nations, 2008, and United Nations Economic Council for Europe, 2020)) were reviewed first. The NSTSP (National Congress on School Transportation, 2015), the NASDPTS emergency and rescue procedures (Tull et al., 2004), the FTA recommended practices (58 C.F.R. § 201, 1993) and the APTA procurement guidelines ((American Public Transportation Association, 2021) were reviewed later.

NFPA 556

NFPA 556 provides an extensive discussion of various motor vehicle fire scenarios, that is scenarios that start in the passenger compartment, the engine compartment or the trunk and scenarios that involve a pool fire beneath the vehicle or are initiated by another external ignition source. For each of these scenarios the guide describes strategies for mitigating the hazard to life of the occupants of the motor vehicle. A distinction is made between fires that involve or are caused by a collision versus those that are not.

To mitigate the hazard to occupants associated with fires that originate in the engine compartment, NFPA 556 recommends one or a combination of the following four strategies.

1. Decrease the ignition propensity of the materials contained in the engine compartment.
2. Decrease the heat release rate of the materials inside the engine compartment.
3. Separate the engine compartment from the passenger compartment by a barrier that either inhibits or prevents the passage of flame and hot gases.
4. Incorporate design improvements that increase the time available for passengers to escape or be rescued.

For the third strategy, NFPA 556 essentially identifies four pathways for the transfer of heat, flame or hot gases from the engine to the passenger compartment.

1. Heat conduction through the firewall.
2. Flow of hot and toxic gases and propagation of flame through ductwork. A distinction is made between ducts made of noncombustible materials and those made of combustible materials. The latter are subject to burn-through while the former are not.
3. Flow of hot and toxic gases and flame propagation through openings around penetrations through the firewall for passage of cables, ducts, etc.
4. Flow of toxic gases and flame propagation through openings created by a collision.

NFPA 556 suggests evaluating the fire resistance of a firewall by exposing it to the standard fire specified in the ASTM E119 (ASTM International, 2020a), which provides procedures for measuring the fire resistance of wall and floor assemblies, roof structures, beams and columns, typically in buildings. Wall, floor/ceiling and roof assemblies are mounted in a vertical or horizontal frame. The frame is placed against an open wall furnace or on top of an open ceiling furnace and is exposed to the standard fire. Figure 1 shows the three fire resistance test furnaces in use at SwRI. The furnace at the top of the picture is used to test floor/ceiling and roof assemblies up to 12 × 16 ft. (3.7 × 4.9 m) in size. The vertical furnace on the left-hand side is used to test wall assemblies up to 12 × 16 ft. (3.7 × 4.9 m) in size. The opening at the top of the small furnace shown on the lower left-hand side measures approximately 5 × 5 ft. (1.52 × 1.52 m). This furnace is used to evaluate through-penetration firestop systems according to ASTM E814 (ASTM International, 2017), for example.

The standard fire is quantified by a specified furnace temperature-time curve (see Figure 2). The furnace temperature is measured with no fewer than nine thermocouples (not fewer than eight for columns), distributed to show the temperature near the specimen. Two end-point criteria are used to determine the fire resistance of a partition (wall assembly not subjected to structural load):

- Heat transmission: Transmission of heat through a partition is quantified based on the unexposed-side temperature measurements. ASTM E119 specifies that at least nine thermocouples must be attached to and distributed over the unexposed surface of the test specimen. The end point for heat transmission is reached when the average temperature rise over the initial temperature of all thermocouple readings reaches 140 °C, or when the temperature rise for any of the individual thermocouple readings exceeds 180 °C.
- Integrity: The integrity end point is reached when hot gases or flames emerging through openings in the specimen are capable of igniting a cotton wad on the unexposed side.

The primary result of an ASTM E119 test is the fire resistance rating, i.e., time rounded to the nearest minute when any of the applicable end-point criteria (heat transmission or integrity) is exceeded.

Figure 1. SwRI's fire resistance furnaces

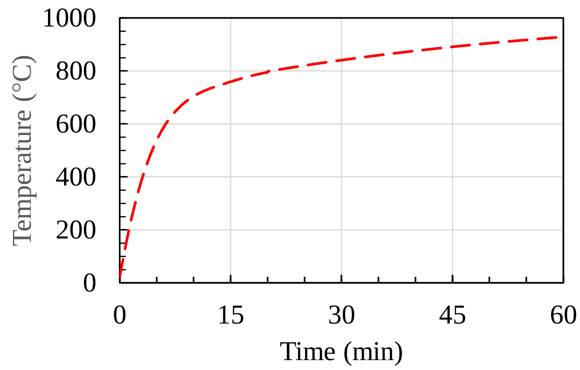


Figure 2. ASTM E119 time-temperature curve

There are several precedents for using ASTM E119 to evaluate the fire resistance of wall or floor assemblies in transportation vehicles.

- The Federal Railroad Administration (FRA) in the U.S. DOT is responsible for the fire safety regulations for passenger trains. The fire performance requirements for materials, products and assemblies that are used in the construction of passenger railcars are described in 49 CFR Part 238. Floor assemblies of passenger railcars are tested according to ASTM E119. The ASTM E119 fire resistance period required shall be consistent with the safe evacuation of a full load of passengers from the vehicle under worst-case conditions but shall not be less than 15 minutes. However, a railroad is not required to use the ASTM E119 test method.
- The jurisdiction of the FRA is limited to railroads that are connected to the national network or provide service between locations in different states. Rapid transit and light rail vehicles and railcars operated by railroads that are not under the jurisdiction of the FRA have to meet local requirements that are usually based on NFPA 130 (National Fire Protection Association, 2020a). The fire performance requirements for floor assemblies of railcars in NFPA 130 are similar to those in 49 CFR Part 238, although there are some important differences. More specifically, ASTM E119 testing is mandatory in the 2020 edition of the NFPA standard and the minimum fire resistance time is 30 minutes for all passenger carrying vehicles, except floor assemblies in automated guideway systems and low floor vehicles, for which the minimum time is 15 minutes.
- The FTA recommends that the firewall in transit buses and vans be tested according to ASTM E119. The most recent update of FTA's fire safety practices was published in the Federal Register on October 20, 1993 at 58 FR 54250 (American Public Transportation Association, 2021). The recommendations provide the following guidance: "The [firewall] should meet the ASTM E119 performance criteria during a nominal test period determined by the transit property. The nominal test period should be twice the maximum expected period of time, under normal circumstances, for a vehicle to come to a complete, safe stop from maximum speed, plus the time necessary to evacuate all passengers from a vehicle to a safe area. The nominal test period should not be less than 15 min. Only one specimen need be tested. A proportional reduction may be made in dimensions of the specimen provided that it represents a true test of its ability to perform

as a barrier against vehicle fires. Penetrations (ducts, piping, etc.) should be designed against acting as conduits for fire and smoke."

- Section TS 5.9 Fire Safety, subsection TS 5.9.1Materials in the APTA transit bus procurement guidelines (American Public Transportation Association, 2021) refer to the recommended FTA fire safety practices discussed in the previous bullet. Section TS 23.1 in the APTA guidelines provides specific requirements for the firewall: "The passenger and propulsion system compartments shall be separated by a fire-resistant bulkhead. This bulkhead shall preclude or retard propagation of a compartment fire into the passenger compartment and shall be in accordance with the Recommended Fire Safety Practices defined in FTA Docket 90A, dated October 20, 1993. Only necessary openings shall be allowed in the bulkhead, and these shall be fire-resistant. Any passageways for the climate control system air shall be separated from the engine compartment by fire-resistant material. Piping through the bulkhead shall have fire-resistant fittings sealed at the bulkhead. Wiring may pass through the bulkhead only if connectors or other means are provided to prevent or retard fire propagation through the bulkhead. Engine access panels in the bulkhead shall be fabricated of fire-resistant material and secured with fire-resistant fasteners. These panels, their fasteners and the bulkhead shall be constructed and reinforced to minimize warping of the panels during a fire that will compromise the integrity of the bulkhead."

In light of the fact that a firewall is most likely to fail at a penetration, a variation of ASTM E814 may be a more appropriate method for evaluating the fire resistance of a firewall. ASTM E814 is used to evaluate firestop systems, which are systems intended to protect openings in ASTM E119-rated fire-resistive walls and floors in buildings that are created to allow the passage of penetrating items such as cables, cable trays, conduits, ducts, pipes, etc. The test is generally identical to ASTM E119 except that thermocouples are attached to the unexposed surface of the materials and devices that are used to seal the opening(s) in the assembly. Two ratings are established for each firestop system. The F rating is based on the time when flame is observed on the unexposed surface, while the T rating is based on the temperature rise as well as flame occurrence on the unexposed side of the firestop system.

ASTM International published several auxiliary standards related to ASTM E814. For example, ASTM E3157 (ASTM International, 2020b) provides detailed information related to the installation of firestop systems, which is helpful in avoiding deficiencies and improving the quality of the installation. Another example is ASTM 2785 (ASTM International, 2014), which describes a test method that is used to evaluate the degradation of a firestop material's performance after exposure to a standardized set of severe environmental conditions. Finally, ASTM E2923 (ASTM International, 2019) provides a method for assessing the longevity of firestop materials based on Arrhenius degradation reaction parameters estimated from differential scanning calorimetry (DSC) data. These auxiliary standards indicate that the design of a firestop system involves more than obtaining the required F or T rating in a fire resistance test conducted according to ASTM E814. As firestop systems in the firewall of motor vehicles are more likely to be exposed to vibrations and extreme temperature and humidity cycles, meeting the auxiliary requirements are bound to be even more challenging than for firestop systems installed in buildings.

UNECE regulations

Försth (2014) lists the principal fire safety requirements for buses in UNECE Regulation No. 107. These requirements can be found in Annex 3 (requirements to be met by all vehicles). Excerpts of the fire safety requirements that are relevant to the present study are copied below:

- "No flammable sound-proofing material or material liable to become impregnated with fuel, lubricant or other combustible material shall be used in the engine compartment unless the material is covered by an impermeable sheet." (Section 7.5.1.1)
- "Precautions shall be taken, either by a suitable layout of the engine compartment or by the provision of drainage orifices, to avoid, so far as possible, the accumulation of fuel, lubricating oil or any other combustible material in any part of the engine compartment." (Section 7.5.1.2)
- "A partition of heat-resisting material shall be fitted between the engine compartment […] and the rest of the vehicle. All fixings, clips, gaskets, etc., used in conjunction with the partition shall be fire resistant." (Section 7.5.1.3)
- "In the case of vehicles having an internal combustion engine […] located to the rear of the driver's compartment, the compartment shall be equipped with an alarm system providing the driver with both an acoustic and a visual signal, and activating the hazard warning signal, in the event of excess temperature in the engine compartment […]" (Section 7.5.1.5)
- "In addition to the alarm system, vehicles [with a capacity exceeding 22 passengers] shall be equipped with a fire suppression system in the engine compartment [... Vehicles with a capacity of 22 passengers or less] may be equipped with a fire suppression system in the engine compartment [...]"

Section 7.5.1.3 in UNECE Regulation No. 107 requires that a fire-resistant barrier be installed to separate the engine compartment from the passenger compartment and other sections of the bus, but does not specify any performance criteria. Finally, Section 5.7 in UNECE Regulation No. 107, which appears to be an updated version of Section 5.6 in ECE 36 (United Nations, 2008), specifies requirements for (1) the number of (emergency) exits based on the number of passengers and crew, and (2) the minimum dimensions and positioning for different types of exits (doors, windows, hatches, etc.)

Försth (2014) also mentions that UNECE Regulation No. 118 (United Nations Economic Council for Europe, 2020), which specifies fire test methods and performance requirements for the assessment of insulation materials used in the engine compartment in terms of their ability to repel fuels or lubricants (Annex 9) and for electrical cables (Annex 10).

National school transportation specifications and procedures

The National school transportation specifications and procedures (NSTSP) provide recommended specifications and procedures for school buses and their operation to ensure the safe, secure and efficient transportation of students. NSTSP recommendations are not regulatory until they are officially adopted by the appropriate state regulatory authority or local school district. The most recent version of the NSTSP (National Congress on School Transportation,

2015) was adopted in 2015 by the 16th National Congress on School Transportation (NCST), which was sponsored by the following national organizations.

- National Association of State Directors of Pupil Transportation Services (NASDPTS)
- National Association for Pupil Transportation (NAPT)
- National School Transportation Association (NSTA)
- School Transportation Section, National Safety Council (NSC)
- School Bus Manufacturers Technical Council (SBMTC)

The suggested applicability of the NSTSP specifications and procedures is either mandatory (shall), advisory (should) or permissive (may). The NSTSP recommendations that are pertinent to this project are briefly discussed in the following sub-sections.

Bus body and chassis specifications

Emergency Exits (p. 39)—All emergency exits shall meet the design and performance requirements in FMVSS 217, even if the exit is not required per FMVSS 217.

Fire Suppression System (p. 42)—Manufacturers may install a suppression system with nozzles in the engine compartment, under the bus, in the electrical panel or under the dashboard.

Floors (p. 42)—Floor coverings shall meet FMVSS 302.

Openings (p. 56)—All openings in the firewall and floorboard shall be sealed (no specific requirements for fire resistance).

Recommended school bus inspection procedures

Note: The NSTSP provides recommendations for school bus inspections and specifies that periodic inspections but does not appear to provide guidance for the frequency of inspections.

Electrical/Battery (p. 104)—Inspection of the electrical system shall include the following

- "Visually inspect all electrical cabling and wiring for chafed, frayed, damaged or burnt insulation."
- "Visually and physically inspect for corroded or loose connections at the battery terminals."
- "Inspect for unsuitable insulation to electrical cabling."
- "Inspect for missing or damaged protective grommets insulating all electrical cables through metal compartment panels. All electrical cabling passing through a metal surface shall pass through an insulated grommet as to provide adequate protection against chaffing and shorting."
- "Visually and physically inspect for any broken or unsecured mounting of electrical components."
- "Visually and physically inspect electrical cabling for securement, routing or any unsecured wiring that may cause chafing or frayed conditions."

Emergency and rescue procedures

For emergency and rescue procedures, the NSPST refers to the NASDPTS procedures, which are briefly discussed below.

School bus seat upholstery fire block test

The NSPST specifies that school bus seats shall pass a fire test that involves exposure to a burning paper bag filled with 196 g of crumpled newsprint placed on the seat (in the first test), below the seat (in the second test) and behind the seat (in the third test). To pass, the seat tested must meet the following criteria in each of the three tests.

- The time from ignition to flameout shall not exceed 8 min.
- Flame shall not spread to an adjacent seat.
- Padding and upholstery mass loss may not exceed 10 percent of the pre-test mass.

The test procedure in ASTM E2574/E2574 M, *Standard Test Method for Fire Testing of School Bus Seat Assemblies,* is identical to the school bus seat upholstery fire block test in the NSPST, except that it uses a gas burner ignition source instead of the paper bag. The net result of this change is that the ASTM version is much more severe, which is evidenced by test results for school bus seats obtained at SwRI (Huczek et al, 2021).

NASDPTS emergency and rescue procedures

The NASDPTS developed *Emergency and Rescue Procedures: A Guideline Manual For School Bus Involvement* for police, fire and ambulance personnel, EMS and other entities designated to respond to school bus emergencies such as a fire. The manual is also used by school systems in developing their own specific emergency plans. Appendix F of the manual provides detailed step-by-step instructions on how to set up drills to practice evacuation through the front or rear door of a school bus. State laws generally require that these drills be conducted (at least) once every year. Although the manual stresses the importance of classroom instruction to prepare for the drills, it is silent on using this as an opportunity to raise students' awareness of the dangers of rapidly developing fires and exposure to toxic smoke.

Research studies

The second part of the literature review a search was conducted of the following publication sets.

- Documents on the NHTSA docket related to the March 7, 1995, Settlement Agreement between General Motors and the U.S. DOT — To identify research projects funded under this agreement that may be relevant to the present study, a search was performed of all documents to find keywords such as "firewall," "bulkhead," "separation," etc. Documents that resulted from this search were inspected to determine in which context the keywords were used. The documents that were found to be relevant were retained for a more detailed review.
- Reports of research studies on the MVFRI web site (www.mvfri.org) – MVFRI was established to fund research projects in post-crash fire safety. The 27 funded research projects include activities in real-world data analysis of impact-induced fires and fuel leakage, experimental testing of fuel systems, evaluation of state-of-the-art technologies for preventing or mitigating fire impact, and more.

- Proceedings of the International Conferences on Fire in Vehicles (FIVE). Since 2010 the SP Technical Research Institute of Sweden has organized international bi-annual conferences on fire safety of vehicles. The program for each conference involved several papers that are relevant to the present study.

Several publications cited in NFPA 556 were also reviewed and a small number were found through a Google Scholar search.

The results of the literature review are grouped in three sections. The first section covers research studies on the initiation and severity (intensity and duration) of engine fires. The second section deals with research on various factors that affect the fire performance of the firewall and implications for its design. The third and last section focuses on vehicle evacuation.

Initiation and severity of engine fires

Strategies to reduce the likelihood of an ignition and decrease the severity of an engine fire in the unlikely event it occurs may not directly affect the design of the firewall, but they do lessen the risk of injuries or fatalities in the passenger compartment.

Preventing or delaying ignition

At the second FIVE conference, Crescenzo (2012) reviewed two major causes of engine fires in buses. The first and most typical cause is from fuel or combustible fluid leaks. The leaking fuels seep or drip on hot engine parts, resulting in a fire. The second cause is an electrical fault. Loose or frayed electrical cables can result in an arc that is capable of igniting nearby combustibles. At the same conference, Ferrone (2012) identified a third cause (mechanical failure) and Wolpert and Engelhaaf (2012) discussed five investigations of bus fires that were caused by one of these three ignition sources. Both Crescenzo and Ferrone stress that frequent inspections, quality maintenance and repairs can go a long way in preventing many of these fires.

Reducing the severity of the engine fire

As part of the settlement with U.S. DOT, GM conducted a series of full-scale fire tests on four crash-tested vehicles at FM Global Research;[5] a passenger van, a rear wheel drive passenger car, a front-wheel drive passenger car and a sports utility vehicle (Jensen & Santrock, 1998b). In three of these tests the fire was initiated in the engine compartments.

- A simulated electrical fault was used to start the fire in the engine compartment of a crash-tested Dodge Caravan (Jensen & Santrock, 1998a), (Santrock, 2001). At 6 to 7 min after ignition, flames spread to the passenger compartments through openings in the windshield. Flames also penetrated through the evaporator and condenser line pass-through closures that were dislodged in the crash test. Flames also penetrated the dashboard through the HVAC air intake where the circulation door was dislodged in the crash. Flame spread through the dashboard was slower than through the windshield. The heat release rate (HRR) versus time curve followed a time-squared profile. The HRR at the time flames penetrated through the windshield (6-7 min) and at the end of the test (11 min) was 0.4 and 1.5 MW, respectively.

[5] Johnston, RI

- A propane torch flame impinging on the HVAC module was used to start the fire in the engine compartment of a rear wheel drive Chevy Camaro (Jensen & Santrock, 2001a; Santrock, 2002b). Flames entered the passenger compartment through openings in the windshield and HVAC module at approximately 5 and 10 min, respectively. At 5 min, the HRR of the engine fire was less than 100 kW. At 11 min the HRR had increased to about 300 kW.
- A fire started in the windshield fluid reservoir after the crash test of a front wheel drive Honda Accord (Jensen & Santrock, 2001b). This ignition scenario was simulated in the fire test (Santrock, 2003). The windshield reservoir ignited 4 to 6 min after ignition of the methanol vapor. Flames spread to the left front wheelhouse panel, left headlamp assembly and left front tire in 10 to 20 min. Flames spread into the engine compartment in 21 to 22 min. Flames spread to passenger compartment through the windshield and pass-through openings in the dashboard in 22 to 27 min. The HRR started rising above the baseline at 21 to 22 min following ignition and reached approximately 400 kW at 27 min.

Several intermediate-scale tests were conducted on HVAC modules to evaluate the effect of using fire-retardant-treated (FR-treated) polymers.

- One untreated control and two FR-treated HVAC modules were exposed to a heptane pool fire (Santrock et al., 2002). The FR treatment caused a 50 percent reduction in the HRR but dramatically increased the CO and smoke production by a factor of 7.5 to 9 and 39 to 47, respectively.
- Three HVAC modules, one untreated control and two with different loadings of FRs, were tested in a vehicle buck (Ohlemiller, 2002). The HVAC modules were damaged to simulate the effects of a collision. The HVAC module was subjected to a 10-min preheat before the ignition source (impinging propane flame) was applied. In the test of the untreated module, flames were visible in the passenger compartment at 135 s following ignition. Maximum HRR was 283 kW and burnout occurred at 283 s. Flames were never observed in the passenger compartment during the tests of the FR-treated modules and maximum HRR was less than 5 kW.

Finally, two full-scale fire tests were conducted of a crashed rear-wheel-drive Chevy Camaro to evaluate the effect of using FR-treated resins in the HVAC module (Santrock, 2002a). The control vehicle contained the original untreated HVAC module. The second vehicle was equipped with an FR-treated version of the module. The ignition source was an electric igniter installed in the air cleaner housing within the engine compartment of the tested vehicles. The FR treatment had no effect on the rate of flame spread from the engine to passenger compartment, but the CO concentration in the test with the FR-treated HVAC module was higher by a factor of 27 compared to the control test.

Suppression

Installing a suppression system appears to be an obvious way to prevent engine fires from spreading to the passenger compartment. Several test series were performed under the GM-U.S. DOT settlement to explore the feasibility of this approach.

- Tests were performed at the NIST to investigate the efficacy of commercially available and emerging fire suppressants in extinguishing engine fires (Hamins, 2000). The suppressants that were evaluated included dry powders, inert suppressants, compressed liquefied halogenated compounds and a number of unique devices. The tests were performed on laboratory-scale test devices and actual vehicles. The results showed that it is highly improbable that an on-board suppression system will be able to extinguish all engine compartment fires. Many suppressant types were found to be impractical for post-collision engine compartment applications.
- Tests were performed to evaluate a prototype suppression system installed in the engine compartment of a Honda Accord (Santrock & Hodges, 2002). The system consisted of two solid propellant gas generators (SPGGs) and two optical detectors. The test vehicle was subjected to a crash in which power steering fluid expelled onto the exhaust manifold ignited. In the crash test the suppression system was not able to extinguish the fire. Subsequently, four static tests were conducted in which an electric heater or power steering fluid sprayed on a hot plate were used as the ignition source. The SPGG suppression system extinguished the fire in two of the four tests and failed to do so in the other two tests.

More recently, two related studies were performed under contract with MVFRI.

- Gunderson and di Marzo (2007) at the University of Maryland reported the development and testing of a nitrogen foam fire suppression system. The purpose of the system is to contain or extinguish a fire that originates in the engine compartment of an automobile after a front-end collision. Full-scale burn tests showed that the system is capable of containing and extinguishing a fire that originates in the engine compartment at the location of the battery.
- Hamins (2007) at NIST identified vehicle suppression research needs based on lessons learnt from previous testing. The report also discusses research needs in related areas such as computer modeling and passive fire protection.

In 2015 SwRI completed a project for NHTSA on motorcoach fire safety (Huczek & Blais, 2015). One goal of this program was to develop and validate procedures and metrics to evaluate current and future engine fire detection and suppression technologies that prevent or delay fire penetration into the passenger compartment of a motorcoach, in order to increase passenger evacuation time. SwRI designed, fabricated, and commissioned a simulated motorcoach engine compartment fixture. It is representative of the motorcoaches currently sold in the United States and is larger than those used typically in Europe, but has comparable air flow. The fixture contains a substantial amount of obstructions to simulate the major components (including the engine) and various hoses, pipes, and electrical wires. Performance criteria were proposed for successfully completing a series of 12 engine compartment fire tests, simulating realistic engine fire scenarios ranging from a small fire involving 12 strips of plastics to a 400-kW diesel spray fire. As part of the development of this procedure for evaluation of engine compartment extinguishing systems, several manufacturers of commercial systems participated and completed the series of tests developed. The systems generally consisted of either dry chemical or wet chemical extinguishing agents as well as hybrid systems that contained both types of technologies. The systems would also typically incorporate a fire detection system to actuate the extinguishing system and the detections systems would rely on a combination of flame detectors, linear heat detectors, and spot heat detectors within the compartment for this purpose. Additional details may be found in the Huczek and Blais paper.

At the first FIVE conference in 2010, Försth (2010) mentioned that Sweden had 6 to 7 complete bus burnouts per year prior to 2004, when insurance companies started requesting that an approved fire suppression system be installed in the engine compartment, and had none since. At the FIVE conference in 2018, Dadon (2018) reported that in 2015, Israel published a new standard (Israeli Standard 6278) requiring fire detection and suppression systems in the engine compartment of buses. He further stated that in the 3 years since its publications, fire statistics do not show any evidence of an effect. In a report documenting the results of an analysis of motorcoach and school bus fires, Meltzer et al. (2016) stated that "An analysis of vehicle age showed that the percent of newer vehicles that caught fire in 2005 was higher than the percent of newer vehicles that caught fire in 2009 or 2013, indicating that implementation of advanced technologies such as fire suppression systems may have a positive effect on fire prevention and mitigation of reportable fires." However, this study unconventionally included passive fire protection measures in the definition of fire suppression systems. This limited information seems to imply that experience with bus engine fire suppression systems is mixed and that more data are needed to support a firm assessment of the efficacy of these systems in operating buses.

Factors affecting firewall performance and design implications

The literature search identified several studies on various aspects of the fire performance and design of firewalls, summarized below.

Mathematical modeling

Mathematical modeling is a useful tool to aid in the design and evaluation of firewalls. It is most useful for evaluating the performance of a firewall in terms of heat conduction. This is because conduction heat transfer calculations are relatively straightforward. The main challenge is to determine the thermal properties of the firewall components. Wichman and co-workers at the University of Michigan developed a method to estimate these properties from measurements in a small scale test using inverse heat transfer calculations (McMasters & Wichman, 2002; Wichman et al., 2001). They obtained good agreement between the results of one-dimensional heat transfer calculations and surface temperature measurements of a larger-scale firewall section exposed to a known heat flux on the engine side

Modeling flows through ducts and openings and penetrations is more complicated. Wittasek and co-workers at Worcester Polytechnic Institute used the computational fluid dynamics model TASCflow in conjunction with a radiation model (Ierardi et al., 1999) to simulate an engine fire and calculate the heat flux to and heat conduction through the fire wall. Adding openings in the fire wall is listed as a topic for future work.

Use of intumescent coatings

Hamins (1998) at NIST performed a study to evaluate the efficacy intumescent paints and caulks in their ability to reduce flame penetrations, heat transfer and transport of toxic gases to the passenger compartment in a post-collision engine fire. Application of an intumescent paint on the engine side reduced conduction heat transfer through the firewall, but failed to close and prevent flames from penetrating even small holes (6 mm) created from the impact associated with the vehicle collision.

Evacuation

Sliepcevich and co-workers reported the results of evacuation studies for a school bus and a motorcoach that were conducted roughly 50 years ago (Sliepcevich et al., 1972a), 1972b). More recently, studies to determine the time needed to evacuate a bus were conducted in Japan (Chung et al., 2016) and China (Liang, 2018). These studies indicate that the time to safely evacuate varies between 0.5 and 2 s per person depending on the number of doors available for egress, whether emergency exits are used, the age of the passengers, whether the evacuation is at night or during the daytime, etc.

In 2009 the Volpe Center published a report that discusses egress times from a full motorcoach after an accident (Pollard & Markos, 2009). This study considered 56 passengers exiting from four different egress paths, with a different number of exits used for each path, and resulted in a range of egress times between approximately 1 to 3 min. This overall timing was used as a basis for a recommended minimum re-ignition time for a hot surface fire suppression test procedure developed as part of a 2015 SwRI research project for NHTSA on the topic of motorcoach fire safety (Huczek & Blais, 2015).

In October 2018 the NAPT organized a school bus fire demonstration and evacuation exercise in collaboration with the Lee’s Summit Fire Department near Kansas City, MO (Schlosser, 2018). Three buses were set up for the demo and exercise. One bus was used to measure the time for 30 volunteers to evacuate. Without seat belts fastened, it took the volunteers 1 min 16 s to evacuate. With seatbelts fastened, evacuation only took 2 s longer. With eyes closed, to simulate the effect of poor visibility, evacuation time increased to 2 min 27 s. The purpose of the evacuation exercises was to show that seatbelts have a negligible effect on the time to evacuate a school bus in the case of an emergency, but that evacuation can be significantly delayed due to poor visibility, for example, in the event of a fire.

A second bus was used to demonstrate how quickly fire spreads. The ignition source was a bale of hay placed in the front door. At 3 min following ignition, dark smoke had filled the bus and temperatures reached about 950 °F (510 °C). Clearly, conditions had become untenable (well) before that time. Firefighters used the third bus to demonstrate how much more difficult it is to safely escape from an overturned bus.

Investigative reports and articles on school bus fires

NTSB report on 2018 Oakland, Iowa, school bus fire

This incident involved a 2018 school bus fire in Oakland, Iowa, in which the 74-year old driver and the only passenger, a 16-year old female student, died. The NTSB investigation report (National Transportation Safety Board, 2019b) provides the following insights.

- The cause and origin of the fire are not known with certainty because of the extensive damage to the engine compartment, but the likely sequence of events was as follows.
    - The driver backed the 2004 model 35530 IC bus into a ditch, blocking the tailpipe.
    - Repeated attempts to accelerate the engine to take the bus back on the road caused the turbocharger to overheat, which then ignited brake, transmission, and power-steering fluids or oil in the engine compartment.
    - Toxic smoke and flame propagated into the passenger compartment.
    - Driver and passenger died from smoke inhalation.
- Additional factors that contributed to the death of the driver and the one student who was on the bus at the time of the incident are the following.
    - The fire burnt through the glassfiber-reinforced plastic (GRP, also known as fiberglass) cowling that covered the engine block extension into the passenger compartment and driver's section through a cut-out in the firewall.
    - Openings in the firewall to allow the passage of fuels and tubing were sealed but not with "fire-resistant" material.
    - The driver was physically impaired and not qualified to operate the bus.

It is unknown why the driver and passenger did not evacuate. Both were found in the front of the bus. The rear exit was not blocked and the student had received training in its use. However, it is speculated that the driver was unable to evacuate due to his impairment and that the student, who was always the first passenger to board the bus and had developed a cordial relationship with the driver, did not want to leave him behind and was overcome by the toxic smoke that started flowing into the passenger compartment.

Selected magazine and web site articles on school bus fires

With an average of about one school bus fire every day, it is easy to find articles in trade magazines and on web sites in which the more dramatic fires are reported. Table 2 gives a short list of school bus fires that started in the engine compartments and are briefly described in trade magazines or on web sites.

Table 2. Short List of School Bus Fires That Started in the Engine Compartments

Date	Location	Students Evacuated	Cause	Damage	Ref.
07/21/21	Presque Isle, ME	8 of 8	Mechanical	Bus destroyed	Acevedo-Vigo, 2021
02/10/21	Sioux Falls, SD	12 of 12	Mechanical	Bus destroyed	[Hannon, 2021
05/16/19	Kansas City, MO	3 of 3	Unknown	Bus destroyed	George, 2019b
01/31/19	Tamarac, FL	16 of 16	Unknown	Bus destroyed	[Hannon, 2019
08/28/18	Kansas City, MO	6 of 6	Mechanical	Bus destroyed	Newton, 2018c
05/02/18	Colorado Springs, CO	7 of 7	Electrical	Fire extinguished	Newton, 2018b
01/24/18	Mobile, AL	20 of 20	Fuel system	Bus destroyed	Newton, 2018a
02/14/17	Saskatoon, SK	6 of 6	Electrical	Bus destroyed	[Larson, 2019
02/08/12	Charlotte, NC	6 of 6	Electrical	Bus destroyed	North Carolina School Bus Safety Web, 2012

What these articles have in common is that they all recognize the quick thinking and heroic efforts of the drivers who managed to evacuate all the children to safety and in one case even managed to use a handheld extinguisher to put the engine fire out.

Conclusions

The following conclusions can be drawn from this review.

- The majority of the studies that were reviewed focus on passenger vehicles and may not be entirely relevant for all buses. For example, a common path for an engine fire to propagate into the passenger compartment of a passenger vehicle is through the HVAC module. This is not the case for buses with the engines in the rear of the vehicles.
- Experience of suppression system effectiveness against bus engine compartment fires is inconclusive. A conference paper presented in 2010 mentions that Sweden had 6 to 7 complete bus burnouts per year prior to 2004, when insurance companies started requesting that an approved fire suppression system be installed in the engine compartment and had none since (Försth, 2010). In 2018 a more recent conference paper reported that fire statistics in Israel do not show any evidence of an effect, three years after publication of a new standard requiring fire detection and suppression systems in the engine compartment of buses (Dadon, 2018).

- The most severe fire specified in existing suppression standards (for example, the 500 kW diesel spray fire in SP Method 4912 [SP Technical Research Institute, 2012]) could be considered as a more realistic representation of the thermal exposure of an engine fire than that specified in ASTM E119.
- Tremendous progress in CFD modeling has been made since the WPI study (Ierardi et al., 1999) was conducted. The necessary computational power and CFD fire modeling software are now readily available to model the complex geometry of bus engine and calculate flows through openings in the firewall with reasonable fidelity. However, this type of numerical modeling requires specialized engineering expertise and the accuracy of the results is affected by uncertainties in the input parameters. Moreover, to obtain results in a reasonable time for such a complex geometry, significant simplifications are needed.
- The NIST study (Hamins, 1998) shows that simply applying an intumescent coating to the fire-exposed surface has little or no effect on preventing the propagation of an engine fire into the passenger compartment through openings in the firewall. A possible approach to address this problem could consist of re-designing penetrations through the firewall based on methods for constructing through-penetration firestops in buildings.
- The evacuation times recorded in the four studies reviewed are very low. However, they do not account for the delays in detecting the fire and making the decision to respond, the time to bring the bus to a stop, complications if the bus is involved in a collision, etc. The minimum fire resistance rating of 15 min specified in FTA's recommended fire safety practices has a safety margin that should be more than sufficient to account for the extra time. Moreover, fire departments generally respond within 15 min.
- The school bus fire demonstration and evacuation exercise in Lee's Summit (Schlosser, 2018) clearly showed the importance of evacuation training in schools. Reports of school bus fires that started in engine compartments in trade magazines and on web sites underscore the critical role of the driver in the process.
- The NTSB report of the Oakland, Iowa, school bus fire identified several firewall openings which could have allowed toxic gases to flow into the passenger compartment and may have contributed to the deaths of the driver and passenger. More specifically, the fiberglass engine cowling on the driver side and unprotected or inadequately protected openings that may allow passage of toxic smoke and flame into the passenger compartment were cited as being problematic.

Task 2: Documentation of selected firewall designs in buses

As previously discussed, the methodology for documenting firewall designs in buses focused on six different site visits, surveying a total of 16 different buses. This section provides further details of the results of those site visits and the resulting documentation. The discussion is separated by vehicle type and position of engine mounting, forward or rear. Examples are provided in the body of the report for the types of observations made during each visit to illustrate a significant point to be further discussed in support of Task 3 of the project. A summary of documented results can be found in Appendixes A to P for each bus. A sketch of most of the buses firewalls and penetrations are provided in the appendices. The exceptions are the motorcoaches and transit buses that were surveyed. Sketches were not prepared for these buses since there were so few visible penetrations.

Several key measurements were taken during each survey. These were all made with a tape measure. LIDAR images were also collected; however, it was not feasible to completely rely on these imaging measurements due to the complex geometry of the engine compartments. Instead, the LIDAR measurements were used in support of the tape measurements.

The procedure at each site was to (1) have preliminary discussions with the onsite personnel, (2) take both tape and LIDAR measurements, and (3) take several photographs to illustrate the observations and measurements and repeat the process after feedback from site staff as necessary.

In terms of measurements, the first setup was to estimate the firewall area by taking several tape measurements of the engine compartment space. Next, all the visible penetrations from the engine compartment to the passenger compartment were sketched and measured. These penetration areas were attempted to be conservatively estimated for all buses and all penetrations. This was done for practical reasons related to ease of measurement and the variation between buses and firewalls in terms of the specific components that formed the penetrations. By taking the same systematic approach for all buses, any minor measurement errors will hopefully be consistent for all the buses and therefore make the relative comparisons more meaningful.

For each bus surveyed, several summary statistics are reported. These include the total estimated firewall area, the total penetration area (sum of each penetration area for a given bus), the total penetration fraction (ratio of total penetration area and firewall area), total number of penetrations and the average area per penetration. These will be compared between bus types at the end of this section of the report.

Documentation of buses with rear-mounted engines

The buses surveyed that consisted of rear-mounted engines were motorcoaches and transit buses. Three different motorcoaches and two different transit buses were surveyed.

For motorcoaches, the primary penetration observed was for the lavatory connections, including the toilet and water fixtures. For these vehicles, the cabling is routed beneath the bus and was well protected in conduit compared to other bus types surveyed.

For transit buses, the primary penetration observed was potential leakage or failure of the engine access panel, which is located in the center of the last row of seating.

Table 3 shows a summary of the firewall penetration statistics determined during the site visits. These vehicles were observed to have the lowest total penetration fraction, compared to the forward-mounted buses (school buses and medium-size buses).

Table 3. Firewall Penetration Data for Rear-Mounted Engines

Bus ID	Bus Type	Engine Mounting Position	Firewall Area (in^2)	Total Penetration Area (in^2)	Total Penetration Fraction (%)	Total Number of Penetrations	Average Penetration Area (in^2)
1994 MCI 102-DL3	Motorcoach	Rear	7228	106.6	1.5	6	17.8
2013 MCI D4505, Cummins ISX engine	Motorcoach	Rear	7228	106.6	1.5	6	17.8
2009 Prevost X3-45, Detroit engine	Motorcoach	Rear	7648	121.6	1.6	7	17.4
2009 Gillig 35-ft. transit bus	Transit	Rear	3247	34.5	1.1	1	34.5
2020 Gillig hybrid 35-ft. transit bus	Transit	Rear	3968	34.5	0.9	1	34.5
		Averages:	5864	80.8	1.3	4	24.4

Motorcoaches

Table 4 shows a summary of the observed penetrations areas and Figure 3 shows selected photographs from one of the surveyed motorcoaches (Prevost X3-45).

Table 4. Firewall Penetration Data for X3-45 Prevost Motorcoach

	Penetration Description	Pentration Area (in^2)
Right Side	Nominal 8-in diameter connection for toilet to lavatory	50.27
	(3) nominal 1-in connections for water/drainage to lavatory	2.36
Center	Possible leakage around nominal 1.5x2.5-ft opening on back wall to PC	24.00
	Possible leakage around recessed space behind mirror in lavatory (1x1.5-ft)	15.00
	Possible leakage around nominal 2x3-ft opening on floor to PC	30.00
	Firewall Area (in^2):	7648.25
	Total Penetration Area (in^2):	121.62
	Total Penetration Fraction (%):	1.6
	Total Number of Penetrations:	7.0
	Average Penetration Area (in^2):	17.4

Rear view of engine compartment


Side view showing toilet tank


View toward rear of cable routing


View toward front of cable routing


Engine access panel


Cavity behind the lavatory mirror

Figure 3. Photograph array of surveyed motorcoach (X3-45 Prevost)

Transit Buses

Figure 4 shows selected photographs from one of the surveyed transit buses (Gillig Diesel) and Table 5 shows a summary of the observed penetrations areas.

Rear view of engine compartment

Engine access panel

Figure 4. Photograph array of surveyed transit bus

Table 5. Firewall Penetration Data for the Transit Buses Surveyed

Penetration Description	Pentration Area (in^2)
Possible leakage around back seat panel above engine block	34.50
Firewall Area (in^2):	3246.75
Total Penetration Area (in^2):	34.50
Total Penetration Fraction (%):	1.1
Total Number of Penetrations:	1.0
Average Penetration Area (in^2):	34.5

Documentation of buses with forward-mounted engines

The buses surveyed that consisted of forward-mounted engines were school buses and medium-sizes buses. Six school buses were surveyed (four longer buses and two shorter buses) and five medium-size buses (Cutaway shuttle buses). These buses had a larger amount of visible penetrations through the firewall, compared to rear-mounted engine buses.

The penetrations consisted of holes in the bulkhead to route cabling, tubing, hose, and air conditioning/heating. The composition of these materials was not able to be determined specifically, but in general consisted of flexible and rigid plastic and rubber components as well as typical cabling composition (jacket/fill/conductor) configurations.

Table 6 shows a summary of the firewall penetration statistics determined during the site visits. These vehicles were observed to have the highest total penetration fraction, compared to the rear-mounted buses (motorcoaches and transit buses).

Table 6. Firewall Penetration Data for Forward-Mounted Engines

Bus ID	Bus Type	Engine Mounting Position	Firewall Area (in^2)	Total Penetration Area (in^2)	Total Penetration Fraction (%)	Total Number of Penetrations	Average Penetration Area (in^2)
2021 Ford E-450 para-transit bus	Medium Size Bus	Forward	695	78.6	11.3	9	8.7
2021 Ford Cutaway para-transit van	Medium Size Bus	Forward	1135	134.1	11.8	10	13.4
2014 Starcraft Prodigy	Medium Size Bus	Forward	831	60.5	7.3	5	12.1
2008 IC Maxxforce DT3200 4×2	Medium Size Bus	Forward	1335	40.6	3.0	26	1.6
2008 Champion Cutaway, GM engine	Medium Size Bus	Forward	1370	46.5	3.4	6	7.7
2021 IC full length school bus	School Bus (Full Length)	Forward	1733	127.5	7.4	62	2.1
2017 Lion 360 school bus	School Bus (Full Length)	Forward	1244	56.1	4.5	15	3.7
2004 IC School Bus (Long)	School Bus (Full Length)	Forward	1467	155.0	10.6	34	4.6
2016 Van-Con Type B wheelchair	School Bus (Medium Size)	Forward	906	55.8	6.2	5	11.2
2016 Microbird MB-11school bus	School Bus (Medium Size)	Forward	756	30.0	4.0	7	4.3
2006 IC School Bus (Short)	School Bus (Reduced Length)	Forward	1479	110.3	7.5	33	3.3
		Averages:	1177	81.4	7.0	19	6.6

School Buses

Figure 5 shows selected photographs from one of the surveyed school buses (2021 IC School Bus – Full-Length) and Table 7 shows a summary of the observed penetrations areas.

Overall view of school bus

Driver (right) side of firewall

Passenger (left) side of firewall

Center of firewall

Figure 5. Photograph array of surveyed school bus

Table 7. Firewall Penetration Data for the 2021 IC Full-Length School Bus Surveyed

	Penetration Description	Pentration Area (in^2)
Left Side	Two 1.5-in diameter hoses (HVAC?) through 2-in diameter penetrations	6.28
	Open slit for conduit penetration for HVAC electrical?	40.00
	(16) 1/4-in diameter holes covered by 1-in covering (some type of tape)	3.14
	(2) 1-in diameter holes covered by 1.5-in covering (some type of tape)	1.57
Right Side	(2) plastic electrical wiring harness connections (4.75x2.5")	23.75
	1.5-in diameter hole with (3) 1/2-in diameter electrical cables (green)	1.77
	2-in connection with plastic conduit (electrical) centered on metal plate (2.75x6.5-in)	3.14
	1-in diameter hole with clear plastic tubing going through	0.79
	(2) 2.5x1.5-in oval holes - just open, nothing routed	2.95
	(2) 1.5-in pipe connections	3.53
	2-in diameter connection with conduit/hose running into pump at right side	3.14
	(3) blank 1-in diameter holes	2.36
	Steering connection - 5x2-in oval	7.85
	Blank 3/4-in connection located next to steering column	0.44
	(4) 1.5-in connections for plastic brake tubing (two 3/4-in diameter tubes and two 3/8-in diameter tubes)	7.07
	(3) 1/2-in connections covered with black grommet	0.59
	1/2-in connection with 1/4-in diameter black rubber tube penetration	0.20
	(4) 3/4-in diameter connections with tubing/covers/open	7.07
	3-in diameter opening with electrical conduit penetration	7.07
	(9) assorted bolt connections, 3/4-in diameter	3.98
	(4) assorted bolt connections, 1/2-in diameter	0.79
	Firewall Area (in^2):	1732.5
	Total Penetration Area (in^2):	127.47
	Total Penetration Fraction (%):	7.4
	Total Number of Penetrations:	62.0
	Average Penetration Area (in^2):	2.1

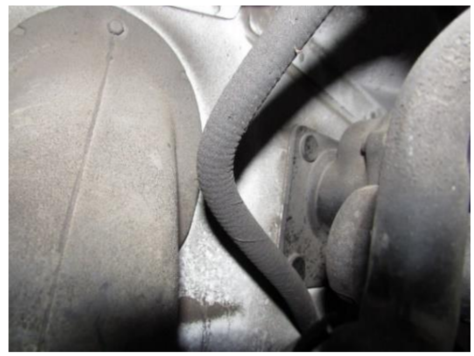
Medium-Size Buses

Figure 6 shows a photograph array of the Champion/GM Cutaway medium-size bus engine compartment surveyed at the Brownsville facility. This bus was very similar to the other medium-size buses surveyed at IDIADA. However, it was possible to observe a few new things for this bus that were not observed for the previous medium-size buses. This had to do with the specific configuration and location of the HVAC ductwork and the engine block cover. Figure 7 shows another photograph array for this bus but focusing on those parts. **Error! Reference source not found.** provides a summary of the observed firewall penetration findings.

Overall view of bus

Overall engine compartment view

Right side view of firewall



View of steering and brake penetrations

Figure 6. Photograph array of Champion/GM Cutaway medium-size Bus

Left side of engine compartment – HVAC

Showing battery under/adjacent HVAC

View of HVAC from interior

View of interior engine cover

Figure 7. Photograph array of Champion/GM Cutaway bus (HVAC and engine cover)

Table 8. Firewall Penetration Data for the Champion/GM Cutaway Medium-Size Bus

	Penetration Description	Pentration Area (in^2)
Left Side	Nominal 1.5-in diameter HVAC outlet into passenger compartment	1.77
Center	Leakage around perimeter of plastic engine cover	26.25
Right Side	Steering column, coming through nominal 4x3-in oval penetration	9.42
	Nominal 1.5-in diameter penetration blank, covered with soft plastic plug	1.77
	Nominal 0.5-in diameter hole with 0.25-in diameter black tubing	0.20
	Nominal 3-in diameter penetration with 3/4-in hose and 3/8-in conduit routed	7.07
	Firewall Area Including Engine Cover (in^2):	1370
	Firewall Area Not Including Engine Cover (in^2):	668
	Total Penetration Area (in^2):	46.47
	Total Penetration Fraction with Engine Cover (%):	3.4
	Total Penetration Fraction without Engine Cover (%):	7.0
	Total Number of Penetrations:	6.0
	Average Penetration Area (in^2):	7.7

Because the interior section of dashboard (included glove compartment and passenger side of vertical section of dashboard) had been removed by the site visit hosts, the potential propagation path was more readily observable. According to the site visit host, and based on proprietary fire event investigations at the operator company, a common fire event scenario for these buses in their fleet is an electrical short of the battery. This failure can then ignite the HVAC housing, which is plastic (likely ABS or PP), and can then fail and easily propagate a fire into the passenger compartment. Before a more catastrophic failure occurs, it may still be possible to transmit products of combustion from an engine compartment fire into the passenger compartment through the existing ductwork outlet (shown in lower left image in Figure 7).

The second most common pathway for the fire/smoke, again according to our site visit host's experience, is through the engine cowling.[6] The cowling was removed for the site visit and is shown in the lower right image of Figure 7. The cowling is on the floor between the driver and doorway of the bus and was plastic (looked to be some sort of glass-reinforced plastic material). It had a foil facing layer of insulation on the engine side for sound deadening and the perimeter of the cowling was sealed with a flexible rubber gasket material. A similar cover was observed for all the medium-size buses and school buses surveyed and is consistent with the cowling on the school bus detailed in the NTSB accident report discussed in Task 1. For the purposes of estimating a penetration area through the cowling, the same approach was taken as explained above for the motorcoaches and transit buses and assumes a ¼-in gap around the perimeter. However, it is worth noting that in a real fire scenario, depending on the size of the engine compartment fire, the entire engine cover could fail catastrophically at some point, just as described for the HVAC module in the preceding paragraph.

[6] The cowling covers an opening in the firewall through which part of the engine can be accessed from within the passenger compartment.

The last newly observed propagation pathway for this type of bus was the supplemental battery compartment, which was located just rear of the main doorway. Figure 8 shows a photograph array of this area. Per the site visit host, this additional battery compartment is quite common in newer medium-size buses and in the event of an electrical short of the main battery in the engine compartment, it is possible to also short out these supplemental batteries and provide a more direct path for fire and smoke into the passenger compartment.

Overall view with battery compartment under wheelchair access door

Close-up view of supplemental batteries and associated cabling

Additional view of battery cable routing

View of bus floor directly above batteries

Figure 8. Photograph array of Champion/GM Cutaway bus (supplemental batteries)

Firewall documentation comparison between bus types

A range of bus types were surveyed. The firewall area varied between 695 to 7,648 in^2, the total penetration fraction varied from 0.9 to 11.8 percent and total number of penetrations varied from 1 to 62. **Error! Not a valid bookmark self-reference.** provides an overall summary of these statistics for each bus surveyed. This list is sorted by total penetration fraction from lowest to highest. The rear-mounted engine buses have the lowest penetration fraction and the school buses and medium-size buses have higher penetration fractions.

Table 10 shows a summary of all the penetration data for school buses. The top table shows the entire list of school buses, the middle table shows only the longer sizes school buses and the bottom table shows only the medium-size school buses. The penetration fraction and total number of penetrations is higher for the longer school buses as compared to medium-size school buses.

Table 11 shows a summary of all the penetration data for medium-size buses. Table 12 shows a summary of the penetration data for motorcoaches and Table 13 shows a summary of the penetration data for transit buses.

Table 13 compares the average firewall statistics for each bus type. In summary, the high-level observations from the documentation of firewalls in the surveyed buses are as follows.

- Rear-mounted transit buses and motorcoaches have the fewest visible penetrations and lowest total penetration fraction.
- Full-length school buses (forward-mounted engines) have the highest number of visible firewall penetrations and highest total penetration fraction.
- Medium-size buses have nearly the same total penetration fraction as full-length school buses with one third of the number of penetrations.

Table 9. Firewall Penetration Data for the All Buses

Bus ID	Bus Type	Engine Mounting Position	Firewall Area (in^2)	Total Penetration Area (in^2)	Total Penetration Fraction (%)	Total Number of Penetrations	Average Penetration Area (in^2)
2020 Gillig hybrid 35-ft. transit bus	Transit	Rear	3968	34.5	0.9	1	34.5
2009 Gillig 35-ft. transit bus	Transit	Rear	3247	34.5	1.1	1	34.5
1994 MCI 102-DL3	Motorcoach	Rear	7228	106.6	1.5	6	17.8
2013 MCI D4505, Cummins ISX engine	Motorcoach	Rear	7228	106.6	1.5	6	17.8
2009 Prevost X3-45, Detroit engine	Motorcoach	Rear	7648	121.6	1.6	7	17.4
2008 IC Maxxforce DT3200 4×2	Medium Size Bus	Forward	1335	40.6	3.0	26	1.6
2008 Champion Cutaway, GM engine	Medium Size Bus	Forward	1370	46.5	3.4	6	7.7
2016 Microbird MB-11school bus	School Bus (Medium Size)	Forward	756	30.0	4.0	7	4.3
2017 Lion 360 school bus	School Bus (Full Length)	Forward	1244	56.1	4.5	15	3.7
2016 Van-Con Type B wheelchair	School Bus (Medium Size)	Forward	906	55.8	6.2	5	11.2
2014 Starcraft Prodigy	Medium Size Bus	Forward	831	60.5	7.3	5	12.1
2021 IC full length school bus	School Bus (Full Length)	Forward	1733	127.5	7.4	62	2.1
2006 IC School Bus (Short)	School Bus (Reduced Length)	Forward	1479	110.3	7.5	33	3.3
2004 IC School Bus (Long)	School Bus (Full Length)	Forward	1467	155.0	10.6	34	4.6
2021 Ford E-450 para-transit bus	Medium Size Bus	Forward	695	78.6	11.3	9	8.7
2021 Ford Cutaway para-transit van	Medium Size Bus	Forward	1135	134.1	11.8	10	13.4
		Averages:	2642	81.2	5.2	15	12.2

Table 10. Firewall Penetration Data for the All School Buses

Bus ID	Bus Type	Engine Mounting Position	Firewall Area (in^2)	Total Penetration Area (in^2)	Total Penetration Fraction (%)	Total Number of Penetrations	Average Penetration Area (in^2)
2021 IC full length school bus	School Bus (Full Length)	Forward	1733	127.5	7.4	62	2.1
2017 Lion 360 school bus	School Bus (Full Length)	Forward	1244	56.1	4.5	15	3.7
2004 IC School Bus (Long)	School Bus (Full Length)	Forward	1467	155.0	10.6	34	4.6
2016 Van-Con Type B wheelchair	School Bus (Medium Size)	Forward	906	55.8	6.2	5	11.2
2016 Microbird MB-11school bus	School Bus (Medium Size)	Forward	756	30.0	4.0	7	4.3
2006 IC School Bus (Short)	School Bus (Reduced Length)	Forward	1479	110.3	7.5	33	3.3
		Averages:	1264	89.1	6.7	26	4.9

Bus ID	Bus Type	Engine Mounting Position	Firewall Area (in^2)	Total Penetration Area (in^2)	Total Penetration Fraction (%)	Total Number of Penetrations	Average Penetration Area (in^2)
2021 IC full length school bus	School Bus (Full Length)	Forward	1733	127.5	7.4	62	2.1
2017 Lion 360 school bus	School Bus (Full Length)	Forward	1244	56.1	4.5	15	3.7
2004 IC School Bus (Long)	School Bus (Full Length)	Forward	1467	155.0	10.6	34	4.6
2006 IC School Bus (Short)	School Bus (Reduced Length)	Forward	1479	110.3	7.5	33	3.3
		Averages:	1481	112.2	7.5	36	3.4

Bus ID	Bus Type	Engine Mounting Position	Firewall Area (in^2)	Total Penetration Area (in^2)	Total Penetration Fraction (%)	Total Number of Penetrations	Average Penetration Area (in^2)
2016 Van-Con Type B wheelchair	School Bus (Medium Size)	Forward	906	55.8	6.2	5	11.2
2016 Microbird MB-11school bus	School Bus (Medium Size)	Forward	756	30.0	4.0	7	4.3
		Averages:	831	42.9	5.1	6	7.7

Table 11. Firewall Penetration Data for the All Medium-Size Buses

Bus ID	Bus Type	Engine Mounting Position	Firewall Area (in^2)	Total Penetration Area (in^2)	Total Penetration Fraction (%)	Total Number of Penetrations	Average Penetration Area (in^2)
2021 Ford E-450 para-transit bus	Medium Size Bus	Forward	695	78.6	11.3	9	8.7
2021 Ford Cutaway para-transit van	Medium Size Bus	Forward	1135	134.1	11.8	10	13.4
2014 Starcraft Prodigy	Medium Size Bus	Forward	831	60.5	7.3	5	12.1
2008 IC Maxxforce DT3200 4×2	Medium Size Bus	Forward	1335	40.6	3.0	26	1.6
2008 Champion Cutaway, GM engine	Medium Size Bus	Forward	1370	46.5	3.4	6	7.7
		Averages:	1073	72.1	7.4	11	8.7

Table 12. Firewall Penetration Data for the Motorcoaches

Bus ID	Bus Type	Engine Mounting Position	Firewall Area (in^2)	Total Penetration Area (in^2)	Total Penetration Fraction (%)	Total Number of Penetrations	Average Penetration Area (in^2)
1994 MCI 102-DL3	Motorcoach	Rear	7228	106.6	1.5	6	17.8
2013 MCI D4505, Cummins ISX engine	Motorcoach	Rear	7228	106.6	1.5	6	17.8
2009 Prevost X3-45, Detroit engine	Motorcoach	Rear	7648	121.6	1.6	7	17.4
		Averages:	7368	111.6	1.5	6	17.6

Table 13. Firewall Penetration Data for the Transit Buses

Bus ID	Bus Type	Engine Mounting Position	Firewall Area (in^2)	Total Penetration Area (in^2)	Total Penetration Fraction (%)	Total Number of Penetrations	Average Penetration Area (in^2)
2009 Gillig 35-ft. transit bus	Transit	Rear	3247	34.5	1.1	1	34.5
2020 Gillig hybrid 35-ft. transit bus	Transit	Rear	3968	34.5	0.9	1	34.5
		Averages:	3608	34.5	1.0	1	34.5

Table 14. Firewall Penetration Data for the All School Buses

Bus Type	Firewall Area (in^2)	Total Penetration Area (in^2)	Total Penetration Fraction (%)	Total Number of Penetrations	Average Penetration Area (in^2)
Transit Bus - Rear Mounted	3608	34.5	1.0	1	34.5
Motorcoach - Rear Mounted	7368	111.6	1.5	6	17.6
School Bus (Medium Size) - Forward Mounted	831	42.9	5.1	6	7.7
Medium Size Bus - Forward Mounted	1073	72.1	7.4	11	8.7
School Bus (Full/Reduced Length) - Forward Mounted	1481	112.2	7.5	36	3.4

Task 3: Engineering evaluation of documented firewalls

Scope of the engineering evaluation

An engineering evaluation was made of the detailed documentation of the firewall designs collected in Task 2 for the 16 buses surveyed during the 6 site visits. The 16 buses with fully documented firewall designs were constructed from 1994 to 2021 and consisted of the following.

- 5 buses with rear-mounted engines
  - 3 motorcoaches with fully documented firewall designs
  - 2 transit buses, (one hybrid)
- 11 buses with forward-mounted engines
  - 5 medium-size buses for general and para-transit use
  - 4 regular size school buses (3 full-length and 1 shorter bus)
  - 2 medium-size school buses

Partially documented firewalls of 4 motorcoaches (2 with engine removed) were also briefly evaluated. The list of buses for which complete documentation was available for an engineering evaluation are given in Table 15.

Table 15. List of Buses With Fully Documented Firewalls

ID	Bus	Year	Site
MC1	MCI 102-DL3 motorcoach	1994	NHTSA VRTC, East Liberty, OH
MC2	MCI D4505 motorcoach	2013	Greyhound Maintenance Center, Dallas, TX
MC3	Prevost X3-45 motorcoach	2019	Greyhound Maintenance Center, Dallas, TX
TB1	2009 Gillig diesel transit bus	2009	First Transit, Brownsville, TX
TB2	2020 Gillig hybrid transit bus	2020	First Transit, Brownsville, TX
SB1	IC full length school bus	2004	NHTSA VRTC, East Liberty, OH
SB2	IC short school bus	2006	NHTSA VRTC, East Liberty, OH
SB3	Lion 360 full length school bus	2017	Applus+ IDIADA, Adelanto, CA
SB4	IC full length school bus	2021	Navistar / IC Bus, San Antonio, TX
SB5	Van-Con Type B medium size wheelchair bus	2016	Applus+ IDIADA, Adelanto, CA
SB6	Microbird MB-11medium size school bus	2016	Applus+ IDIADA, Adelanto, CA
MB1	Champion medium size bus	2008	First Transit, Brownsville, TX
MB2	IC Maxxforce DT3200 medium size bus	2008	Navistar / IC Bus, San Antonio, TX
MB3	Starcraft Prodigy medium size bus	2014	Applus+ IDIADA, Adelanto, CA
MB4	Ford medium size para-transit bus	2021	FirstGroup, Tampa, FL
MB5	Ford E-450 medium size para-transit bus	2021	FirstGroup, Tampa, FL

Focus of the engineering evaluation

The focus of the engineering evaluation was to:

- Evaluate the firewalls against benchmark design features related to the ability of a partition to mitigate propagation of an engine fire into the passenger compartment.
- Quantify openings and gaps in the partition design that could hamper the ability to mitigate fire propagation.
- Identify potential improvements of current partition designs for mitigating propagation of engine fires into the passenger compartment.
- Consider practical considerations and design constraints for improved partitions to mitigate propagation of engine compartment fires into the passenger compartment.

Benchmark firewall features

Initially, the intent was to perform a quantitative assessment of the surveyed firewalls but after reviewing the information collected during the first few site visits it became clear that a more qualitative approach had to be used. The principal reason for this change was that it would have been nearly impossible to make a quantitative and objective assessment of trade-offs. (For example, how does one compare a firewall with a 20 small penetrations to a firewall with only 2 penetrations but double the total penetrated area?) The final approach involves rating each of the 16 documented firewalls against a benchmark design. The benchmark firewall is characterized by the presence of a number of features that have a positive impact on its ability to prevent or delay propagation of a fire from the engine compartment into the passenger compartment. The following desirable features were identified in Task 1 and later refined in Tasks 2 and 3.

- Sandwich construction consisting of a double sheet metal wall with noncombustible thermal insulation in the cavity, designed to maintain integrity in a collision.
- Open ducts penetrating the firewall are sealed with fire-rated caulking around the outer perimeter of the penetration, made of metal and provided with a mechanism to prevent hot and toxic gases from flowing into the passenger compartment.
- Cables, tubing, etc. are routed through fire-resistant penetrations or connectors, couplings, etc., mounted on the firewall surface.
- Remaining openings are protected with covers of non-combustible material and/or sealed with resilient firestopping material.

Results of the engineering evaluations

Firewall area and total area and number of penetrations

Intuitively one would expect that an engine fire is more likely to spread through a firewall that is large in area than through a firewall that is small in area because the former is more likely to have weak spots where heat transferred by conduction can raise the temperature on the passenger side and cause combustible components to ignite. Likewise, toxic smoke and hot gases or flame are more likely to flow into the passenger compartment for a firewall that has a higher number of penetrations and/or total penetrated area.

The following four figures provide a comparison of the firewall area and total area and number of penetrations for the 16 buses that were surveyed in Task 2. Figure 9 indicates that the firewalls in motorcoaches, and up to a lesser extent transit buses, are much larger than the firewalls in school buses and medium-size buses. This can be explained by the fact that vehicles and engine size are larger in motorcoaches and transit buses. However, as discussed in more detail in the next few sections, the negative effect of the larger firewall size is offset by the fact that firewalls in motorcoaches are not in direct contact with the passenger compartment but separate the engine from an intermediate space, which acts as a buffer. Figure 10 indicates that the total penetrated area in motorcoaches is comparable to that in the full-size school buses. However, Figure 12 clearly shows that the number of penetrations is much smaller in motorcoaches, which implies that they are much larger and therefore easier to seal. This is consistent with the fact that the total penetrated area is much smaller for motorcoaches compared to the other buses, as shown in Figure 11.

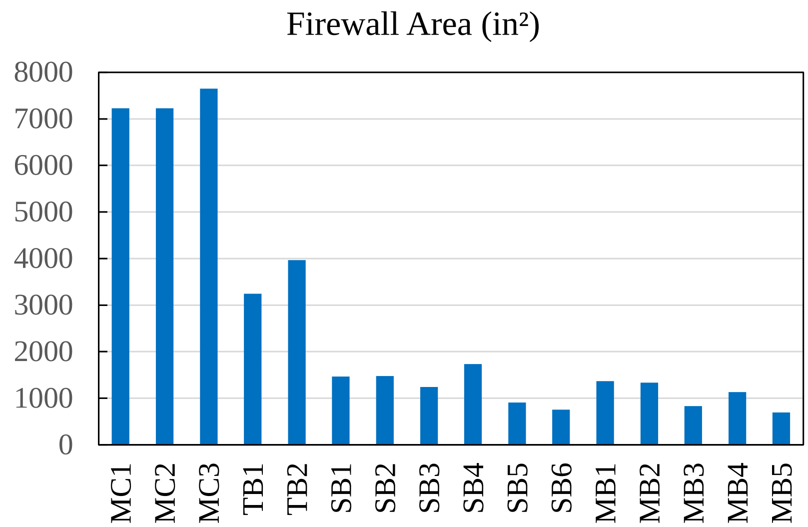


Figure 9. Firewall area for the 16 buses surveyed

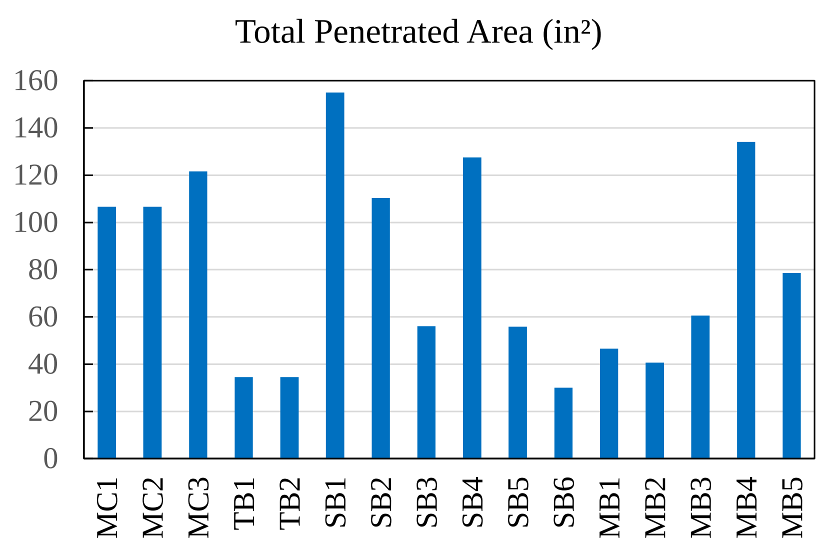


Figure 10. Total penetrated area for the 16 firewalls documented

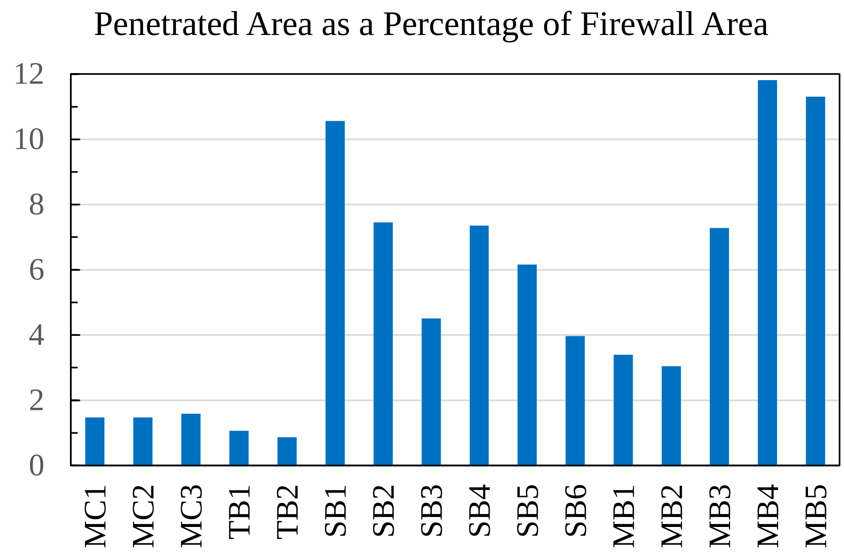


Figure 11. Penetrated area as a percentage of firewall area for the 16 buses surveyed

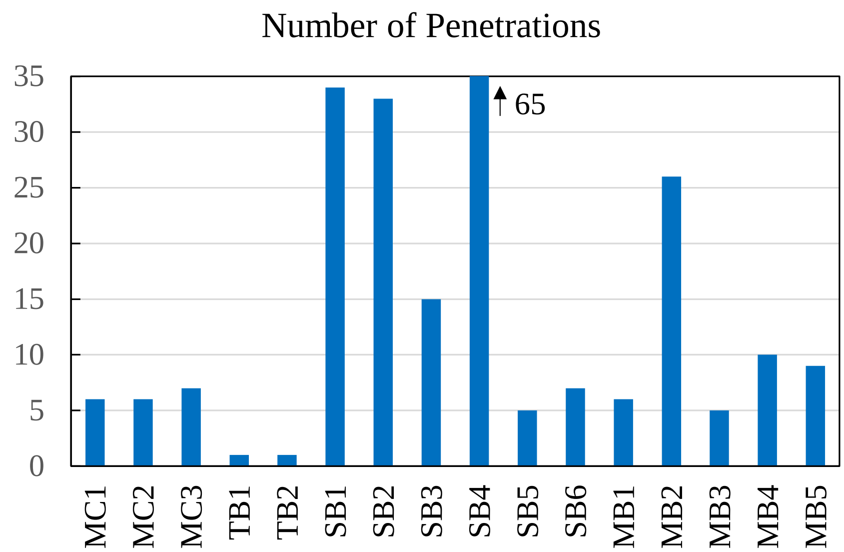


Figure 12. Number of penetrations for the 16 firewalls documented

Firewall evaluations for buses with rear-mounted engines

Evaluation against the benchmark

All inspected motorcoaches and transit buses had rear-mounted engines. In addition to the area and penetration number statistics, Figure 13 summarizes the benchmark comparison for the three motorcoaches and two transit buses that were surveyed in Task 2. The cells colored in green indicate where the surveyed firewall meets the benchmark criteria, while those colored in red correspond to benchmark criteria that are not met. Strictly speaking, the firewalls in the surveyed motorcoaches and transit buses do not consist of a double metal wall. However, as discussed in the previous section, the engine in these vehicles is separated by an intermediate space.

Nevertheless, the cells for the double wall construction benchmark criterion (single wall construction = "N") are colored in orange because of the hatches that were observed during motorcoach and transit bus inspections as shown in Figure 3 (bottom left) and Figure 4 (right), respectively. Also, the "other hazards" criterion was added to capture hazardous conditions that were observed in selected school and medium-size buses.

	MC1	MC2	MC3	TB1	TB2
Forward-mounted engine	N	N	N	N	N
Single wall construction	N	N	N	N	N
No thermal insulation	Y	Y	Y	Y	Y
HVAC penetrates firewall	N	N	N	N	N
Cowling in passenger area	N	N	N	N	N
Openings with grommets	N	N	N	N	N
Unprotected openings	N	N	N	N	N
Other hazards	N	N	N	N	N
Firewall area (in^2)	7228	7228	7648	3247	3968
Area of penetrations (in^2)	106.6	106.6	121.6	34.5	34.5
Penetrated/firewall area (%)	1.5	1.5	1.6	1.1	0.9
Number of penetrations	6	6	7	1	1

Figure 13. Benchmark firewall comparison for motorcoaches and transit buses

Discussion

All inspected motorcoaches and transit buses had very few direct penetrations through the firewall (see Appendices D and E). For motorcoaches, most of the electrical wiring, tubing and ductwork is routed through the luggage storage space below the floor. Ventilation ducts, water lines and septic tank connection for the toilet are exceptions but these penetrations are relatively easy to seal. Transit buses do not have a toilet in the back and have a second exit/entrance in the center of the vehicle that will facilitate evacuation in the event of a fire. However, both transit buses that were inspected had a row of GRP seats in the back located above a hatch in the floor. The hatch may provide a path for toxic smoke and fire to spread to the passenger compartment if the cover is not properly sealed. A similar hatch was also observed in the motorcoaches, although in this case a breach of the cover would not provide a path to flammable GRP seating. Based on discussions during the site visits, it appears that increasing frequency and rigor of preventative maintenance in the engine compartment is regarded as a more efficient and cost-effective approach to reduce the risk for engine fires that could pose a threat to the passengers. Others in the industry have made similar observations Crescenzo, 2012; Ferrone, 2012; George, 2019a0.

Firewall evaluations for buses with forward-mounted engines

Evaluation against the benchmark

Figure 14 and Figure 15 summarize the benchmark comparisons for the six school buses and five medium-size buses surveyed in Task 2, respectively. From a comparison with Figure 13, it is evident from the prevalence of red colored cells in these two figures that firewalls in buses with forward-mounted engines have a much inferior benchmark rating than firewalls in buses with rear-mounted engines. The orange colored cells labeled "N" (or "Y") refer to cases where the rating is probably "N" (or "Y") but could not be determined with certainty. The orange colored cells labeled "C" refer to large quantities of loose exposed electrical cables, wires and connectors located under the dashboard of SB5 and MB2. The cell labeled "B" for MB1 is colored red because of the fire hazard associated with the battery, which seems to be located under inadequately protected openings in the floor of the bus. Finally, the cells labeled “B” for MB4 and MB5 are colored orange because of the additional ignition hazard associated with the location of the battery under the driver’s seat. In this case, however, this is likely to be offset by the ability to continue supplying power to instruments, lighting, etc. inside the vehicle after electrical failure. Figure 14 also shows that the medium-size school buses (SB5 and SB6) are slightly better in meeting benchmark criteria than full size school buses.

	SB1	**SB2**	**SB3**	**SB4**	**SB5**	**SB6**
Forward-mounted engine	Y	Y	Y	Y	Y	Y
Single wall construction	Y	Y	Y	Y	Y	Y
No thermal insulation	Y	Y	Y	Y	Y	N
HVAC penetrates firewall	Y	Y	Y	Y	Y	Y
Cowling in passenger area	Y	Y	N	Y	N	N
Openings with grommets	N	N	N	Y	Y	N
Unprotected openings	Y	Y	Y	Y	Y	Y
Other hazards	N	N	N	N	C	N
Firewall area (in^2)	1467	1479	1244	1733	906	756
Area of penetrations (in^2)	155.0	110.3	56.1	127.5	55.8	30.0
Penetrated/firewall area (%)	10.6	7.5	4.5	7.4	6.2	4.0
Number of penetrations	34	33	15	62	5	7

Figure 14. Benchmark firewall comparison for school buses

	MB1	**MB2**	**MB3**	**MB4**	**MB5**
Forward-mounted engine	Y	Y	Y	Y	Y
Single wall construction	Y	Y	Y	Y	Y
No thermal insulation	Y	Y	Y	Y	Y
HVAC penetrates firewall	Y	Y	Y	Y	Y
Cowling in passenger area	Y	N	Y	N	Y
Openings with grommets	N	N	N	N	N
Unprotected openings	Y	N	Y	Y	Y
Other hazards	B	C	N	B	B
Firewall area (in^2)	1370	1335	831	1135	695
Area of penetrations (in^2)	46.5	40.6	60.5	134.1	78.6
Penetrated/firewall area (%)	3.4	3.0	7.3	11.8	11.3
Number of penetrations	6	26	5	10	9

Figure 15. Benchmark firewall comparison for the medium-size buses

Discussion

All school buses and medium-size buses that were inspected had a forward-mounted engine. The proximity of the engine to the driver and the principal exit raises the importance of the firewall's ability to mitigate fire spread from the engine to the passenger compartment. However, hardening firewalls in buses with forward-mounted engines has several challenges that are discussed in the next four sub-sections.

Thermal insulation

The firewall consists of sheet metal, which, at best, is provided with insulation over part of the surface (as in SB6, for example). However, the insulation appears to serve primarily as a sound-deadening material. A possible improvement involves the use of noncombustible high-temperature insulation, but this may present some challenges in terms of installation and sound-deadening ability. An alternative method to provide protection, which has the potential of being effective in significantly reducing the conduction heat transfer from an engine fire (Hamins, 1998), involves the use of an intumescent coating applied to the sheet metal on the engine side of the firewall. This method may be practical to implement in new buses, but retrofitting existing buses may present significant practical and logistical challenges. Moreover, durability of such coatings in the cyclical and relatively harsh outdoor environment would need to be investigated.

Engine cowling

Ignition and burn-through of the engine cowling was a significant contributing factor to the loss of life in the Oakland, Iowa, school bus fire (National Transportation Safety Board, 2019b). Some school buses and medium-size buses that were surveyed in Task 2 have an engine that extends into the passenger compartment. In those buses, the part of the engine inside the passenger compartment is covered with a cowling (see Figure 16 for some examples). These cowlings are designed so that it is easy to temporarily remove them for periodic inspections, maintenance and repairs. Some may cease to provide any meaningful resistance to the spread of an engine fire into the passenger compartment after years of use due to the wear and tear on the cowling gasket. Replacing the cowling with a fire-resistant design has the potential of significantly reducing the hazard to the driver and passengers in the event of an engine fire and is an improvement that may be relatively easy to implement.

Unprotected openings

Firewalls have (small) openings to allow passage of electrical cables, tubing, etc. In some cases, penetrating items are inside a metal conduit that is welded or flanged and screwed to the sheet metal of the firewall. Quite often, however, the penetrating items are routed through an open hole in the sheet metal of the firewall. A rubber or plastic grommet is used to prevent the sharp edges of the sheet metal from chafing and cutting into the penetrating items. An example is shown in Figure 17(a). However, grommets are subject to wear and tear because of vibrations and constantly changing environmental conditions and may fail. This has resulted in fires caused by severed fluid lines and shorts of damaged electrical cables (Gray, 2019). In addition, this type of penetrations does not prevent the passage of toxic smoke and hot gases or flame through the firewall. A possible fix is to route the penetrating items through a pipe flange that is screwed to the sheet metal of the firewall and to fill the annular space around the penetrating items with fire-resistant sealant. Figure 17(b) illustrates the use of a practical method to seal the opening with firestopping material. Note that in this illustrative example, the fire performance characteristics of the sealant are not known.

Figure 16. Pictures of engine extension and cowling in MB1 (a-c) and MB5 (d)

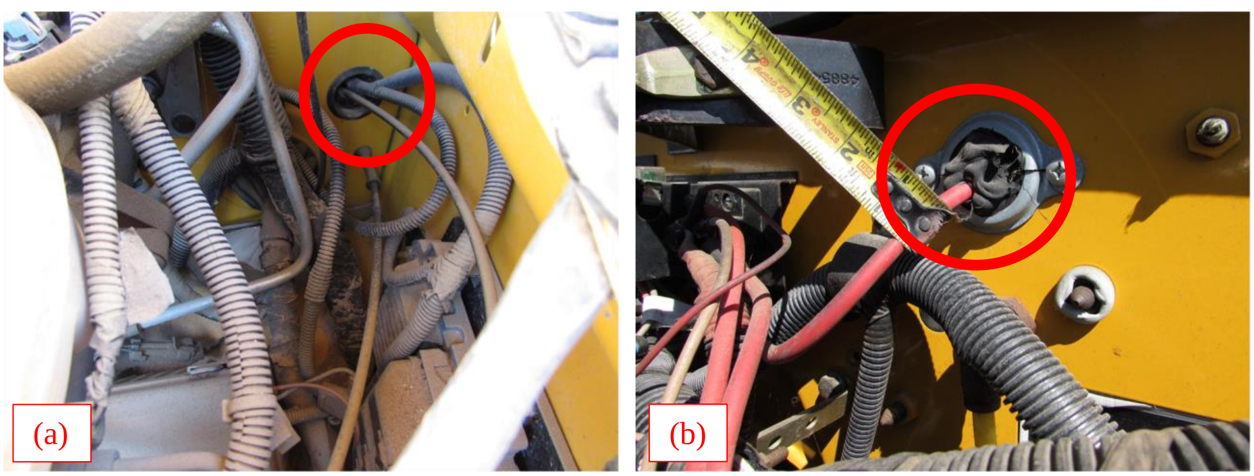


Figure 17. Open firewall penetration with grommet (a) and sealed penetration (b)

HVAC system

Hot and toxic products of combustion from a forward-mounted engine can easily flow into the passenger compartment through the HVAC system. Moreover, the ductwork and components of the system are made of plastics, which are usually subject to burn-through. Research conducted under the settlement between GM and U.S. DOT has shown that the use of HVAC components treated with fire retardants may improve the flammability, but also increase the production of toxic gases (Santrock et al., 2002; Santrock, 2002a, 2002b). Consequently, a possible improvement would require the use of metal HVAC system components and ductwork, with noncombustible insulation on the engine side. A fire damper could be used to prevent toxic smoke from flowing into the passenger compartment. This would require a significant design change on most buses.

Effect of a collision

Post-collision forward-mounted engine fires may be more likely to result in casualties than fires in buses that are not involved in a collision. A frontal collision may enlarge existing or create new openings in the firewall of a bus with a forward-mounted engine, but the effects on the hazard to passengers is hard to quantify. However, the engine fire tests on crashed vehicles conducted at FM under the GM-U.S. DOT settlement seem to indicate that the effect of a frontal collision on fire spread through the firewall may not be as significant as on fire propagation into the passenger compartment through the (damaged) windshield. Defense-in-depth and compensatory measures

Defense-in-depth is an approach that is used by the U.S. Nuclear Regulatory Commission (NRC) to minimize the risk for a catastrophic event (core damage and early release of radiation or hazardous materials in the atmosphere) in a nuclear power plant as a result of an accident such as a fire. In the context of fire safety, defense-in-depth involves creating multiple independent and redundant layers of protection to compensate for human and mechanical failures so that no single layer is exclusively relied upon. Conformance to the defense-in-depth safety concept requires that an adequate level of fire safety must be maintained whenever a fire protection feature is disabled or impaired. Sometimes these impairments cannot be easily corrected and in those cases the NRC may allow the use of compensatory measures, which are fire-safety enhancements that are intended to provide reasonable assurance that any degradation in fire safety caused by an impairment will be compensated until permanent corrective actions can be completed.

The following defense-in-depth and compensatory measures can be explored to enhance fire safety and compensate for deficiencies in the firewall design in the event of an engine fire.

- Measures to prevent engine fires and mitigate their impact:
    - Implement more frequent and rigorous preventative engine inspection, maintenance and repair programs, which has proven benefits (Ferrone, 2012; George, 2019; Crescenzo, 2018).
    - Install incipient fire detection system in the engine compartment (nuisance alarms are a potential issue that needs to be addressed).
    - Install active fire suppression system in the engine compartment (already used in motorcoaches and transit buses, with mixed experience).

- Improved training and education of drivers and passengers to promote rapid response and facilitate safe evacuation in bus fires:
    - Develop standardized school bus evacuation drills simulating different realistic scenarios to supplement or replace existing guidelines for such drills. For example, the emergency and rescue procedures developed by NASDPTS provide detailed step-by-step instructions on how to set up drills to practice evacuation through the front or rear door of a school bus, but these need to be supplemented with 21st century instructional materials. Steps should be taken to ensure that drills be conducted by every school district, at least twice a year.
    - The instructional materials available and/or to be developed for school buses could serve as the basis for materials that provide instructions to passengers of motorcoaches, medium-size buses and vans on what to do in case of an emergency (similar to the safety instructions on passenger aircraft).

Conclusions

The following conclusions can be drawn from this engineering evaluation.

- Engine fires are much less likely to spread to the passenger compartment in buses with a rear-mounted engine (motorcoaches and transit buses) compared to buses with a forward-mounted engine (school buses and medium-size buses) because firewalls in buses with a rear-mounted engine are not in direct contact with the passenger compartment and have far fewer penetrations with a much smaller total penetrated area.
- Furthermore, buses with a rear-mounted engine have much better benchmark ratings than buses with forward-mounted engines, which can be seen at a glance from the difference in dominant color in Figure 13 (green) versus Figure 14 and Figure 15 (red).
- The proximity of a forward-mounted engine to the driver and the principal exit raises the importance of the firewall's ability to mitigate fire spread from the engine to the passenger compartment in a school and medium-size bus. Firewall designs features that can mitigate the spread of flames and gases have been identified, as follows.
    - Thermal-resistant coating of the firewall in which the engine side of the firewall is covered with an intumescent coating.
    - Periodically inspect the cowling and perform repairs as needed or replace deficient or inadequate cowling with a fire-resistant design (inspections and repairs are relatively easy to do in existing buses, but replacement is much more complicated).
    - Penetrating items such as electrical cables and tubing routed through a pipe flange that is screwed to the sheet metal of the firewall as shown in as shown in Figure 17(b), instead of through an unprotected opening in the firewall with a grommet as shown in Figure 17(a). Annular space around the penetrating items filled with fire-resistant sealant.
    - HVAC system components and ductwork made with metal components (in lieu of plastic parts); fire damper installed to prevent toxic smoke from flowing into the passenger compartment.

- Defense-in-depth and compensatory measures are identified that have the potential to enhance fire safety. Examples are the implementation of frequent and rigorous preventative engine inspection, maintenance and repair programs and development of updated instructional materials to facilitate safe egress in the event of a bus fire.

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Appendix A: Firewall Documentation of 2020 Gillig Diesel-Hybrid 35-ft Transit Bus

Figure A-1 shows a photograph array of the Gillig-Hybrid engine compartment surveyed at the Brownsville, Texas, facility. Table A-1 provides a summary of the observed firewall penetration findings. There were no visible penetrations. However, there is a hatch that makes some type of connection between compartments and the estimated penetration listed in Table A-1 assumes a ¼-in gap forming around the perimeter of this hatch area in the event of a fire.

Overall view

Overall rear view

Right rear view

Interior view

Figure A-1. Photograph array for Gillig-Hybrid transit bus

Table A-1. Summary of Penetrations for Gillig-Hybrid Transit Bus

Penetration Description	Pentration Area (in^2)
Possible leakage around back seat panel above engine block	34.50
Firewall Area (in^2):	3968.25
Total Penetration Area (in^2):	34.50
Total Penetration Fraction (%):	0.9
Total Number of Penetrations:	1.0
Average Penetration Area (in^2):	34.5

Appendix B: Firewall Documentation of 2009 Gillig Diesel 35-ft Transit Bus

Figure B-1 shows a photograph array of the Gillig-Diesel engine compartment surveyed at the Brownsville, Texas, facility. Table B-1 provides a summary of the observed firewall penetration findings. There were no visible penetrations. However, there is a hatch that makes some type of connection between compartments and the estimated penetration listed in B-1 assumes a ¼-in gap forming around the perimeter of this hatch area in the event of a fire.

Overall view

Overall rear view

Interior view

Back seat access panel to engine block

Figure B-1. Photograph array for Gillig-Diesel Transit Bus

Table B-1. Summary of Penetrations for Gillig-Diesel Transit Bus

Penetration Description	Pentration Area (in^2)
Possible leakage around back seat panel above engine block	34.50
Firewall Area (in^2):	3246.75
Total Penetration Area (in^2):	34.50
Total Penetration Fraction (%):	1.1
Total Number of Penetrations:	1.0
Average Penetration Area (in^2):	34.5

Appendix C: Firewall Documentation of 1994 MCI 102-DL3 Motorcoach

Figure C-1 shows a photograph array of the MCI bus engine compartment. With the exception of the lavatory connections, there were no observable penetrations for this bus, which is consistent with the information received from the manufacturer prior to this field site visit. Table C-1 shows a summary of the penetration statistics. These are taken as the same for the MCI coach described in Appendix D.

Overall view

Top part of firewall on left side

Top part of firewall on left side (close-up)

Top part of firewall on center/right side

Figure C-1. Photograph array for MCI bus surveyed at VRTC

Table C-1. Summary of Penetrations for MCI Motorcoach Surveyed at VRTC

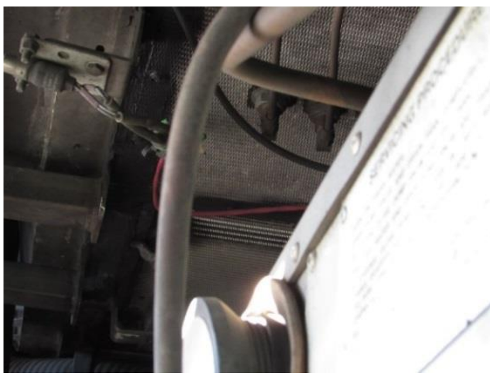
	Penetration Description	Pentration Area (in^2)
Right Side	Nominal 8-in diameter connection for toilet to lavatory	50.27
	(3) nominal 1-in connections for water/drainage to lavatory	2.36
Center	Possible leakage around nominal 1.5x2.5-ft opening on back wall to PC	24.00
	Possible leakage around nominal 2x3-ft opening on floor to PC	30.00
	Firewall Area (in^2):	7228
	Total Penetration Area (in^2):	106.62
	Total Penetration Fraction (%):	1.5
	Total Number of Penetrations:	6.0
	Average Penetration Area (in^2):	17.8

Appendix D: Firewall Documentation of 2013 MCI D4505 Motorcoach

Figure D-1 shows a photograph array of the MCI D4505 motorcoach engine compartment. Table D-1 provides a summary of the observed firewall penetration findings. The only visible penetrations are related to the lavatory connections. However, there are also two hatches that make some type of connection between compartments and the estimated penetration listed in Table D-1 assumes a ¼-in gap forming around the perimeter of this hatch area in the event of a fire. This is likely a conservative assumption for a flame spread path. If these leakage perimeter areas are taken away, then the penetration area is reduced from 1.5 percent to 0.73 percent of the area of the firewall.

Overall view of rear

View of right side



Lavatory Water Connections

Toilet Connection

Figure D-1. Photograph array for MCI D4505 motorcoach

Table D-1. Summary of Penetrations for MCI D4505 Motorcoach

	Penetration Description	Pentration Area (in^2)
Right Side	Nominal 8-in diameter connection for toilet to lavatory	50.27
	(3) nominal 1-in connections for water/drainage to lavatory	2.36
Center	Possible leakage around nominal 1.5x2.5-ft opening on back wall to PC	24.00
	Possible leakage around nominal 2x3-ft opening on floor to PC	30.00
	Firewall Area (in^2):	7228
	Total Penetration Area (in^2):	106.62
	Total Penetration Fraction (%):	1.5
	Total Number of Penetrations:	6.0
	Average Penetration Area (in^2):	17.8

Appendix E: Firewall Documentation of 2009 Prevost X3-45 Motorcoach

Figure E-1 shows a photograph array of the Prevost motorcoach engine compartment surveyed at the Greyhound facility. Table E-1 provides a summary of the observed firewall penetration findings. The only visible penetrations are related to the lavatory connections. However, there are also two hatches that make some type of connection between compartments and the estimated penetration listed in Table 4 assumes a ¼-in gap forming around the perimeter of this hatch area in the event of a fire. This is likely a conservative assumption for a flame spread path. If these leakage perimeter areas are taken away, then the penetration area is reduced from 1.5 percent to 0.69 percent of the area of the firewall.

Overall view

Left rear side with fan compartment

Right rear side with electrical box

Cable routing through luggage area

Figure E-1. Photograph array for Prevost motorcoach surveyed at Greyhound facility

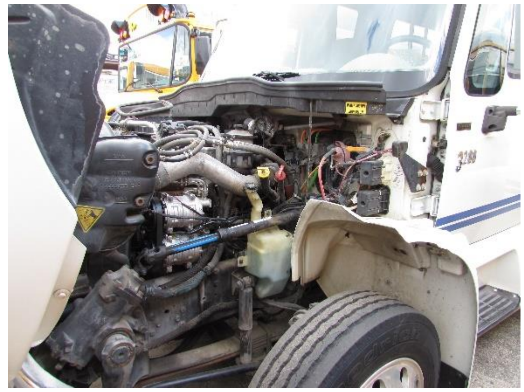
Table E-1. Summary of Penetrations for Prevost Motorcoach Surveyed at Greyhound Facility

	Penetration Description	Pentration Area (in^2)
Right Side	Nominal 8-in diameter connection for toilet to lavatory	50.27
	(3) nominal 1-in connections for water/drainage to lavatory	2.36
Center	Possible leakage around nominal 1.5x2.5-ft opening on back wall to PC	24.00
	Possible leakage around recessed space behind mirror in lavatory (1x1.5-ft)	15.00
	Possible leakage around nominal 2x3-ft opening on floor to PC	30.00
	Firewall Area (in^2):	7648.25
	Total Penetration Area (in^2):	121.62
	Total Penetration Fraction (%):	1.6
	Total Number of Penetrations:	7.0
	Average Penetration Area (in^2):	17.4

Appendix F: Firewall Documentation of 2008 IC Maxxforce DT3200 4×2 Commercial Bus

Figure F-1 shows a photograph array of the IC commercial bus engine compartment surveyed at Navistar/IC Bus. Table F-1 provides a summary of the observed firewall penetration findings. Figure F-2 shows a schematic of the observed penetrations.

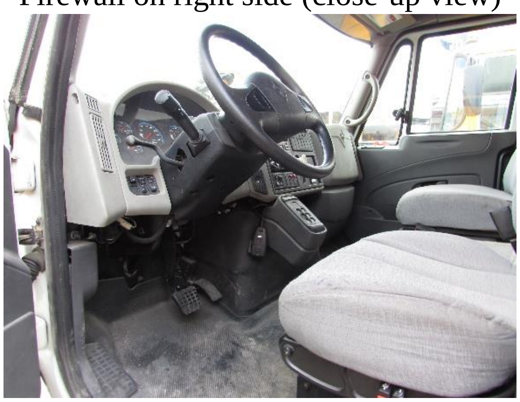
Overall view



Firewall on right side

Firewall on right side (close-up view)

Penetrations on left side



Driver's location – Interior

Interior – View from below steering wheel

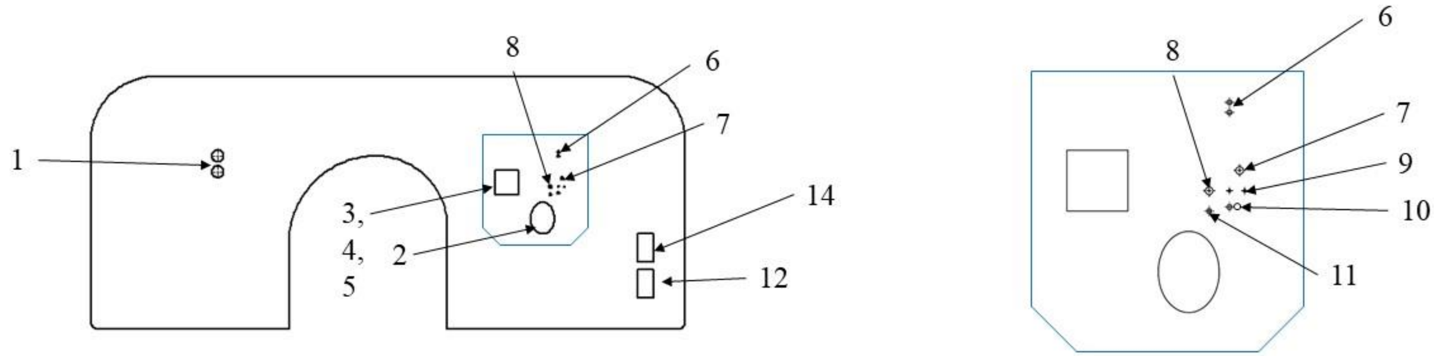
Figure F-1. Photograph array for IC commercial bus surveyed at Navistar/IC Bus

Table F-1. Summary of Penetrations for IC Commercial Bus

	Penetration Description	Pentration Area (in^2)
Left Side	(2) 1.5-in diameter holes with pipes/hose for AC	3.53
Right Side	Steering column, nominal 3x4-in oval penetration	9.42
	Brake connection - 3x3-in metal plate mounting	9.00
	Brake connections - (6) 3/8-in diameter tubing penetrations	0.66
	Brake connections - (2) 3/4-in diameter tubing penetrations	0.88
	(2) 1/4-diameter red wires	0.39
	3/8-in diameter yellow tubing	0.11
	3/8-in diameter black tubing	0.11
	(2) 1/8-in red wires	0.02
	(2) 1/4-in diameter holes	0.39
	1/4-in diameter black wire	0.20
	1.5-in diameter hose connected to yellow ball valve (coolant hose?)	1.77
	(2) 1/4-in diameter wires	0.10
	(2) wiring plate connections, each 2x3.5-in	14.00
	Firewall Area (in^2):	1335
	Total Penetration Area (in^2):	40.60
	Total Penetration Fraction (%):	3.0
	Total Number of Penetrations:	26.0
	Average Penetration Area (in^2):	1.6

	Penetration No.	Penetration Description	Pentration Area (in^2)
Left Side	1	(2) 1.5-in diameter holes with pipes/hose for AC	3.53
Right Side	2	Steering column, nominal 3x4-in oval penetration	9.4
	3	Brake connection - 3x3-in metal plate mounting	9.0
	4	Brake connections - (6) 3/8-in diameter tubing penetrations	0.7
	5	Brake connections - (2) 3/4-in diameter tubing penetrations	0.9
	6	(2) 1/4-diameter red wires	0.4
	7	3/8-in diameter yellow tubing	0.1
	8	3/8-in diameter black tubing	0.1
	9	(2) 1/8-in red wires	0.0
	10	(2) 1/4-in diameter holes	0.4
	11	1/4-in diameter black wire	0.2
	12	1.5-in diameter hose connected to yellow ball valve (coolant hose?)	1.8
	13	(2) 1/4-in diameter wires	0.1
	14	(2) wiring plate connections, each 2x3.5-in	14.0

Firewall Area (in^2):	1335.0
Total Penetration Area (in^2):	40.6
Total Penetration Fraction (%):	3.0
Total Number of Penetrations:	26.0
Average Penetration Area (in^2):	1.6



NS-IC- 2008 IC Maxxforce DT3200 4×2

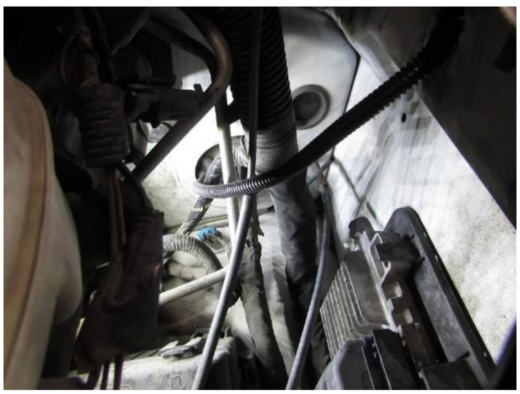
Figure F-2. Schematic of penetrations for IC commercial bus surveyed at Navistar/IC Bus

Appendix G: Firewall Documentation of 2008 Champion/GM Cutaway Medium-Size Bus

Figure G-1 shows a photographic array of the Champion/GM Cutaway bus engine compartment surveyed at the Brownsville, Texas, facility. This bus was very similar to the other medium-size buses surveyed at IDIADA. However, it was possible to observe a few new things for this bus that were not observed for the previous medium-size buses. This had to do with the specific configuration and location of the HVAC ductwork and the engine block cover. Figure G-2 shows another photograph array for this bus, but focusing on those parts. Table G-1 provides a summary of the observed firewall penetration findings.

Overall view of bus

Overall engine compartment view



Rght side view of firewall

View of steering and brake penetrations

Figure G-1. Photograph array for Champion/GM Cutaway Bus

Because the interior section of dashboard had been removed by the site visit hosts, the potential propagation path was more readily observable. According to the site visit host, a common fire event scenario for these buses in their fleet is an electrical short of the battery, which can then ignite the HVAC housing, which is plastic (likely ABS or PP), and can then fail and easily propagate a fire into the passenger compartment. Before a more catastrophic failure occurs, it may still be possible to transmit products of combustion from an engine compartment fire into the passenger compartment through the existing ductwork outlet (shown in lower left image in Figure G-2).

Left side of engine compartment – HVAC

Showing battery under/adjacent HVAC

View of HVAC from interior

View of interior engine cover

Figure G-2. Photograph array for Champion/GM Cutaway bus (HVAC and engine cover)

The second most common pathway for the fire/smoke, again according to our site visit host's experience, is through the engine cover. This cover was removed for the site visit and is shown in the lower right image of Figure G-2. This cover is on the floor between the driver and doorway of the bus and was plastic (looked to be some sort of glass-reinforced plastic material). It had a foil facing layer of insulation on the engine side for sound deadening and the perimeter of the cover was sealed with a flexible rubber gasket material. For the purposes of estimating a penetration area through this cover, the same approach was taken as explained above for the motorcoaches and transit buses and assumes a ¼-in gap around the perimeter. However, it is worth noting that in a real fire scenario, depending on the size of the engine compartment fire, the entire engine cover could fail catastrophically at some point, just as described for the HVAC module in the preceding paragraph.

The last newly observed propagation pathway for this type of bus was the supplemental battery compartment, which was located just rear of the main doorway. Figure G-3 shows a photograph array of this area. Per the site visit host, this additional battery compartment is quite common in newer medium-size buses and in the event of an electrical short of the main battery in the engine compartment, it is possible to also short out these supplemental batteries and provide a more direct path for fire and smoke into the passenger compartment.

Overall view with battery compartment under wheelchair access Door

Close-up view of supplemental batteries and associated Cabling

Additional view of battery cable routing

View of bus floor directly above batteries

Figure G-3. Photograph array for Champion/GM Cutaway bus (supplemental batteries)

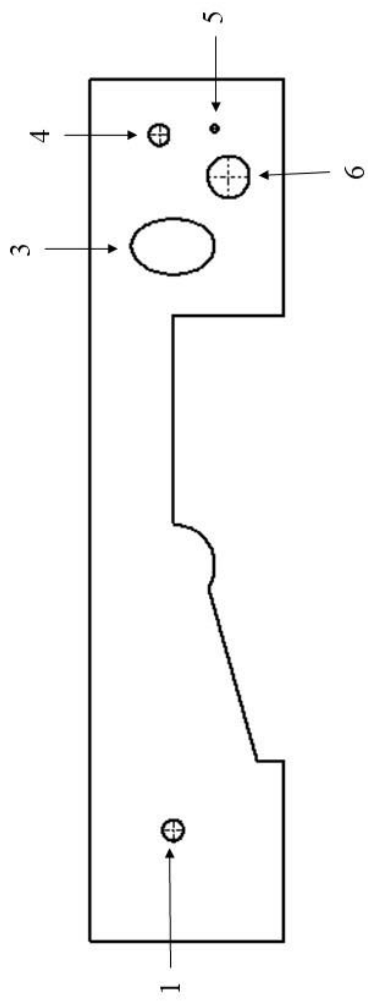
Table G-1. Summary of Penetrations for Champion/GM Cutaway Bus

	Penetration Description	Pentration Area (in^2)
Left Side	Nominal 1.5-in diameter HVAC outlet into passenger compartment	1.77
Center	Leakage around perimeter of plastic engine cover	26.25
Right Side	Steering column, coming through nominal 4x3-in oval penetration	9.42
	Nominal 1.5-in diameter penetration blank, covered with soft plastic plug	1.77
	Nominal 0.5-in diameter hole with 0.25-in diameter black tubing	0.20
	Nominal 3-in diameter penetration with 3/4-in hose and 3/8-in conduit routed	7.07
	Firewall Area Including Engine Cover (in^2):	1370
	Firewall Area Not Including Engine Cover (in^2):	668
	Total Penetration Area (in^2):	46.47
	Total Penetration Fraction with Engine Cover (%):	3.4
	Total Penetration Fraction without Engine Cover (%):	7.0
	Total Number of Penetrations:	6.0
	Average Penetration Area (in^2):	7.7

Figure G-4 shows a schematic of the documented penetrations during the site visit.

	Penetration No.	Penetration Description	Pentration Area (in^2)
Left Side	1	Nominal 1.5-in diameter HVAC outlet into passenger compartment	1.77
Center	2	Leakage around perimeter of plastic engine cover	26.25
Right Side	3	Steering column, coming through nominal 4x3-in oval penetration	9.42
	4	Nominal 1.5-in diameter penetration blank, covered with soft plastic plug	1.77
	5	Nominal 0.5-in diameter hole with 0.25-in diameter black tubing	0.20
	6	Nominal 3-in diameter penetration with 3/4-in hose and 3/8-in conduit routed	7.07

Firewall Area Including Engine Cover (in^2):	1370.0
Firewall Area Not Including Engine Cover (in^2):	668.0
Total Penetration Area (in^2):	46.5
Total Penetration Fraction with Engine Cover (%):	3.4
Total Penetration Fraction without Engine Cover (%):	7.0
Total Number of Penetrations:	6.0
Average Penetration Area (in^2):	7.7



FG-BR 2008 Champion Cutaway, GM Engine

Figure G-4. Schematic of penetrations for Champion/GM Cutaway bus

Appendix H: Firewall Documentation of 2016 Microbird MB-11 School Bus

Figure H-1 shows a photograph array of the Microbird bus engine compartment surveyed at IDIADA. Table H-1 provides a summary of the observed firewall penetration findings. Figure H-1 shows a schematic of the documented penetrations during the site visit.

Overall view

Overall view (close-up)

Firewall on right side

Firewall on left side

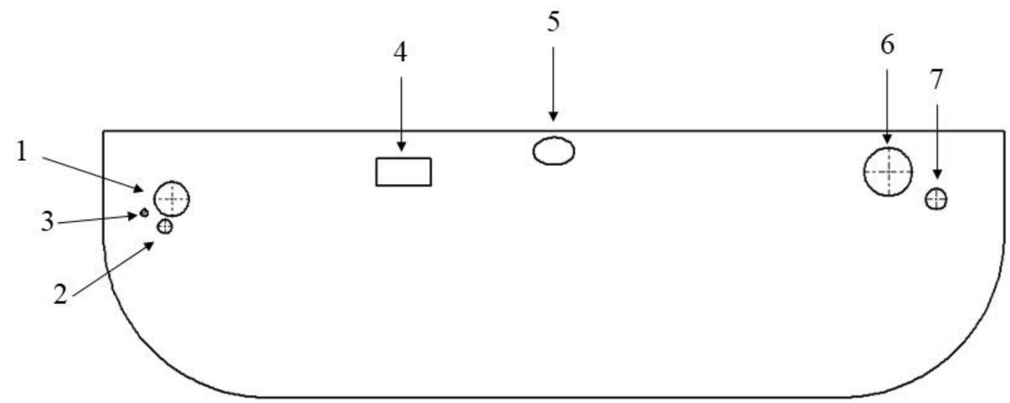
Figure H-1. Photograph array for Microbird bus surveyed at IDIADA

Table H-1. Summary of Penetrations for IDIADA-Microbird Bus

	Penetration Description	Pentration Area (in^2)
Left Side	Nominal 2.5-in dia hole with 1-in dia hose	4.91
	Nominal 1-in dia hole with (2) 1/8-in wires	0.79
	Nominal 1/2-in dia hole with 1.4-in tubing	0.20
Center	Rectangular cutout (4x2-in) with (2) 1-in dia piping attached to manifold	8
	Oval cutout (2x3 in) with (2) 1.25-in dia hose connections	4.71
Right Side	Steering column, coming through nominal 3.5-in diameter penetration	9.62
	Nominal 1.5-in diameter penetration with 1/4-in tubing	1.77
	Firewall Area (in^2):	756
	Total Penetration Area (in^2):	29.99
	Total Penetration Fraction (%):	4.0
	Total Number of Penetrations:	7.0
	Average Penetration Area (in^2):	4.3

	Penetration No.	Penetration Description	Pentration Area (in^2)
Left Side	1	Nominal 2.5-in dia hole with 1-in dia hose	4.91
	2	Nominal 1-in dia hole with (2) 1/8-in wires	0.79
	3	Nominal 1/2-in dia hole with 1.4-in tubing	0.20
Center	4	Rectangular cutout (4x2-in) with (2) 1-in dia piping attached to manifold	8
	5	Oval cutout (2x3 in) with (2) 1.25-in dia hose connections	4.71
Right Side	6	Steering column, coming through nominal 3.5-in diameter penetration	9.62
	7	Nominal 1.5-in diameter penetration with 1/4-in tubing	1.77

Firewall Area (in^2):	756.0
Total Penetration Area (in^2):	30.0
Total Penetration Fraction (%):	4.0
Total Number of Penetrations:	7.0
Average Penetration Area (in^2):	4.3



IDIADA- 2016 Microbird MB-11 School Bus

Figure H-2. Schematics of penetrations for Microbird bus surveyed at IDIADA

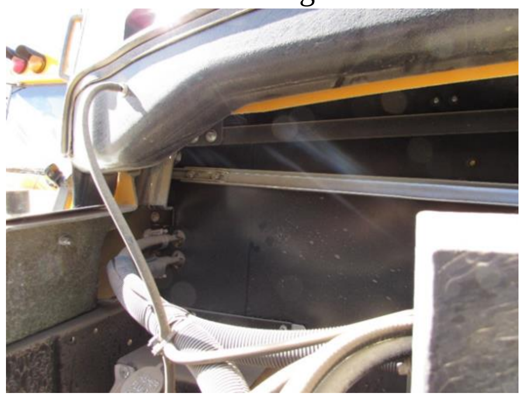
Appendix I: Firewall Documentation of 2017 Lion 360 School Full-Length Bus

Figure I-1 shows a photograph array of the Lion bus engine compartment surveyed at IDIADA. Table I-1 provides a summary of the observed firewall penetration findings. Figure I-2 shows a sketch of the observed penetrations documented at the site visit.

Overall view

Firewall on right side

Firewall on left/center side



Firewall on left side

Figure I-1. Photograph array for Lion bus surveyed at IDIADA

Table I-1. Summary of Penetrations for IDIADA-Lion Bus

	Penetration Description	Pentration Area (in^2)
Left Side	(4) 3/4" copper tubing through 1-in diameter penetrations	3.14
	Opening for conduit? (can't really tell if there is something similar to VRTC bus)	0.00
Right Side	Steering column, nominal 4x3-in oval penetration	9.42
	Brake assembly, nominal 3x6-in penetration cutout for mounting of brake component	18.00
	Wiring Panel - black wire - common ground - 2-in penetration connection	3.14
	Wiring Panel - red wire - 2-in penetration connection	3.14
	Wiring Panel - 1.25-in dia wire in 2-in penetration connection	3.14
	Wiring Panel - larger wiring harnesses (3.5x3.5 in)	12.25
	Conduit under wiring panel - 1.5-in dia	1.77
	(3) 3/8-in diameter tubing penetrations below wiring panel	0.33
	Coolant valve connection, rubber hose - 1.5-in dia	1.77
	Firewall Area (in^2):	1244
	Total Penetration Area (in^2):	56.11
	Total Penetration Fraction (%):	4.5
	Total Number of Penetrations:	15.0
	Average Penetration Area (in^2):	3.7

	Penetration No.	Penetration Description	Pentration Area (in^2)
Left Side	1	(4) 3/4" copper tubing through 1-in diameter penetrations	3.14
Right Side	2	Steering column, nominal 4x3-in oval penetration	9.42
	3	Brake assembly, nominal 3x6-in penetration cutout for mounting of brake component	18.00
	4	Wiring Panel - black wire - common ground - 2-in penetration connection	3.14
	5	Wiring Panel - red wire - 2-in penetration connection	3.14
	6	Wiring Panel - 1.25-in dia wire in 2-in penetration connection	3.14
	7	Wiring Panel - larger wiring harnesses (3.5x3.5 in)	12.25
	8	Conduit under wiring panel - 1.5-in dia	1.77
	9	(3) 3/8-in diameter tubing penetrations below wiring panel	0.33
	10	Coolant valve connection, rubber hose - 1.5-in dia	1.77

Firewall Area (in2):	1244.0
Total Penetration Area (in2):	56.1
Total Penetration Fraction (%):	4.5
Total Number of Penetrations:	15.0
Average Penetration Area (in2):	3.7

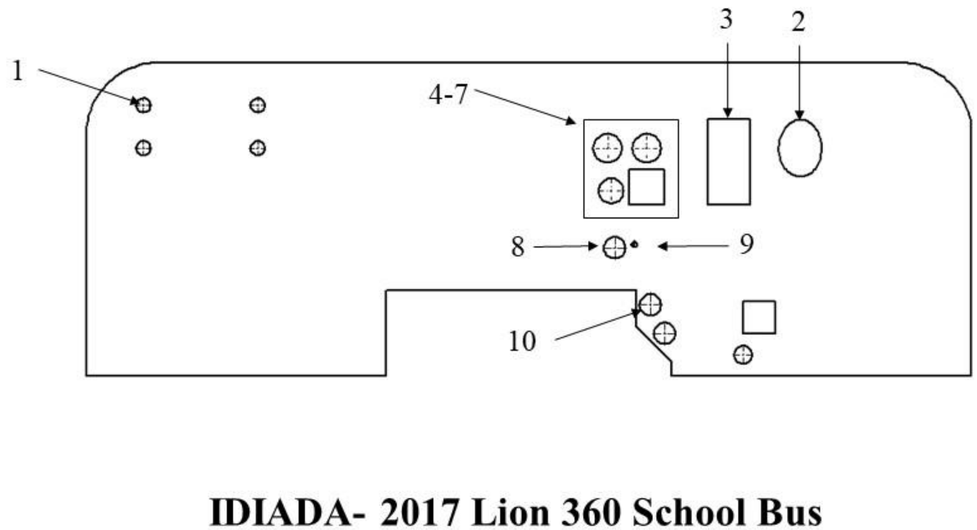


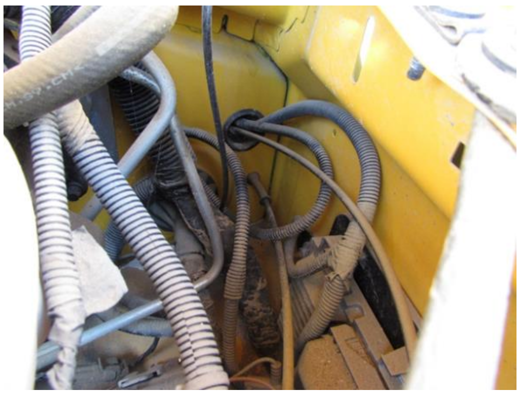
Figure I-2. Schematic of penetrations for Lion bus surveyed at IDIADA

Appendix J: Firewall Documentation of 2016 Van Con Type B Wheelchair Short School Bus

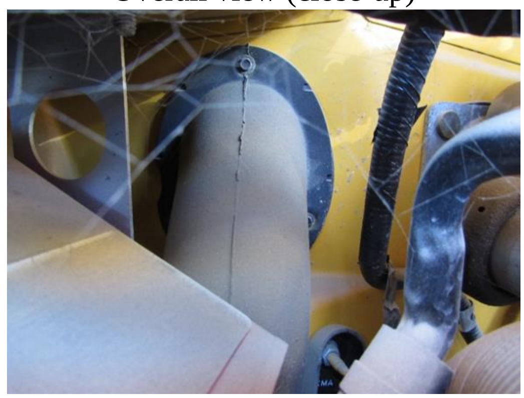
Figure J-1 shows a photograph array of the Van Con bus engine compartment surveyed at IDIADA. Table J-1 provides a summary of the observed firewall penetration findings. Figure J-2 shows a schematic of the observed penetrations.

Overall view

Overall view (close-up)



Firewall on right side



Firewall on right side (steering penetration)

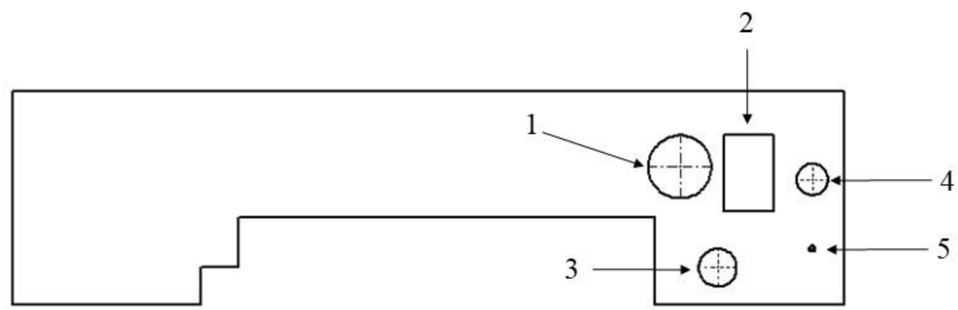
Figure J-1. Photograph array for Van Con Bus surveyed at IDIADA

Table J-1. Summary of Penetrations for IDIADA-Van Con Bus

	Penetration Description	Pentration Area (in^2)
Right Side	Steering column, nominal 5-in diameter penetration	19.63
	Brake assembly, nominal 4x6-in penetration cutout for mounting of brake component	24.00
	Nominal 3-in diameter penetration with pipe/hose	7.07
	Nominal 2.5-in diameter penetration cutout with 2 wire conduits (1/2 and 3/8-in) and 1 tubing (3/8-in)	4.91
	Nominal ½-in diameter penetration with 3/8-in tubing	0.20
	Firewall Area (in^2):	906
	Total Penetration Area (in^2):	55.81
	Total Penetration Fraction (%):	6.2
	Total Number of Penetrations:	5.0
	Average Penetration Area (in^2):	11.2

	Penetration No	Penetration Description	Pentration Area (in^2)
Right Side	1	Steering column, nominal 5-in diameter penetration	19.63
	2	Brake assembly, nominal 4x6-in penetration cutout for mounting of brake component	24.00
	3	Nominal 3-in diameter penetration with pipe/hose	7.07
	4	Nominal 2.5-in diameter penetration cutout with 2 wire conduits (1/2 and 3/8-in) and 1 tubing (3/8-in)	4.91
	5	Nominal ½-in diameter penetration with 3/8-in tubing	0.20

Firewall Area (in^2):	906.0
Total Penetration Area (in^2):	55.8
Total Penetration Fraction (%):	6.2
Total Number of Penetrations:	5.0
Average Penetration Area (in^2):	11.2



IDIADA- 2016 Van-Con Type B Wheelchair

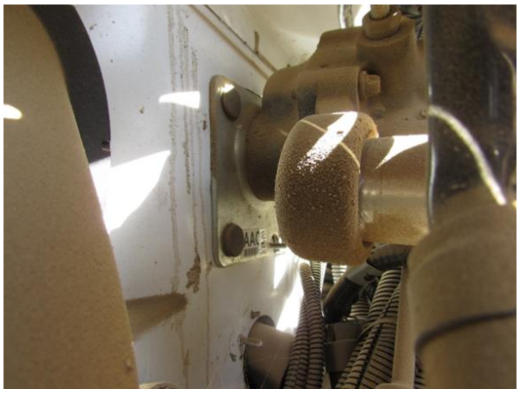
Figure J-2. Schematic of penetrations for Van Con bus surveyed at IDIADA

Appendix K: Firewall Documentation of 2014 Starcraft Prodigy Medium-Size Bus

Figure K-1 shows a photograph array of the Starcraft bus engine compartment surveyed at IDIADA. Table K-1 provides a summary of the observed firewall penetration findings. Figure K-2 shows a sketch of the observed penetrations during the site visit.

Overall view

Overall view (close-up)



Firewall on right side (brake connection)

Firewall on right side

Figure K-1. Photograph array for Starcraft Bus surveyed at IDIADA

Table K-1. Summary of Penetrations for IDIADA-Starcraft Bus

	Penetration Description	Pentration Area (in^2)
Right Side	Steering column, nominal 5-in diameter penetration	19.63
	Brake assembly, nominal 4x6-in penetration cutout for mounting of brake compone	24.00
	Nominal 3-in diameter penetration with pipe/hose	7.07
	Nominal 3.5-in diameter penetration with hose	9.62
	Nominal ½-in diameter penetration with ¼-in tubing	0.20
	Firewall Area (in^2):	831
	Total Penetration Area (in^2):	60.52
	Total Penetration Fraction (%):	7.3
	Total Number of Penetrations:	5.0
	Average Penetration Area (in^2):	12.1

	Penetration No.	Penetration Description	Pentration Area (in^2)
Right Side	1	Steering column, nominal 5-in diameter penetration	19.6
	2	Brake assembly, nominal 4x6-in penetration cutout for mounting of brake component	24.0
	3	Nominal 3-in diameter penetration with pipe/hose	7.1
	4	Nominal 3.5-in diameter penetration with hose	9.6
	5	Nominal ½-in diameter penetration with ¼-in tubing	0.2

Firewall Area (in^2):	831.0
Total Penetration Area (in^2):	60.5
Total Penetration Fraction (%):	7.3
Total Number of Penetrations:	5.0
Average Penetration Area (in^2):	12.1

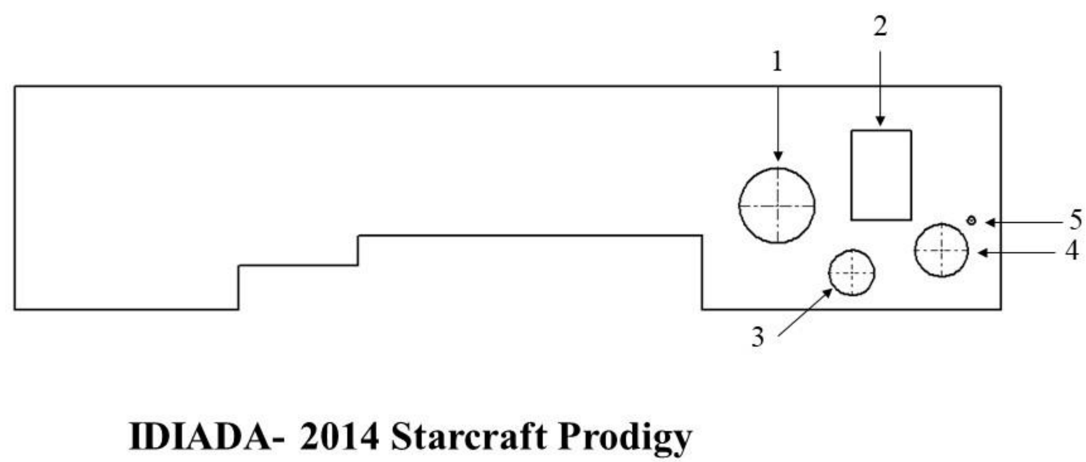


Figure K-2. Schematic of penetrations for Starcraft bus surveyed at IDIADA

Appendix L: Firewall Documentation of 2021 IC Full-Length School Bus

Figure L-1 shows a photograph array of the IC school bus engine compartment. Table L-1 provides a summary of the observed firewall penetration findings. The school bus surveyed looked very similar to the one surveyed at VRTC. Figure L-2 shows a schematic of the penetrations observed during the site visit.

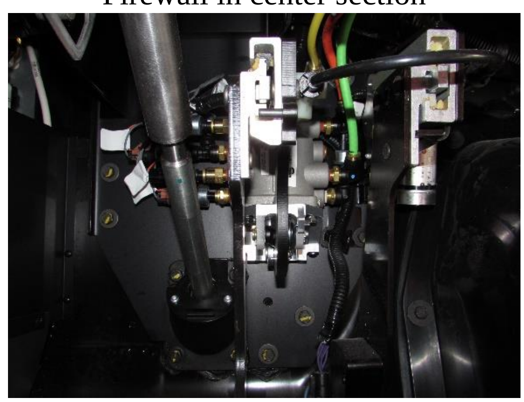
Overall view

Firewall on right side

Firewall on left side

Firewall in center section

Driver's location – Interior



Interior – View from below steering wheel

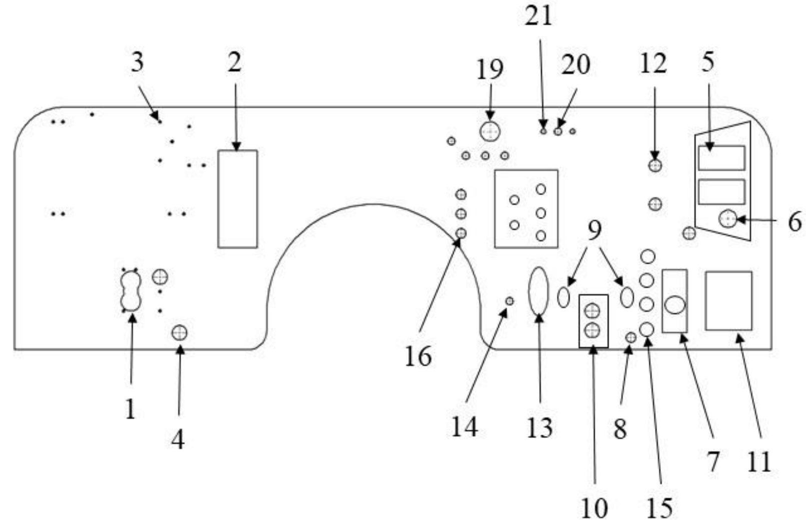
Figure L-1. Photograph array for IC school bus at Navistar/IC Bus

Table L-1. Summary of Penetrations for IC School Bus at Navistar/IC Bus

	Penetration Description	Pentration Area (in^2)
Left Side	Two 1.5-in diameter hoses (HVAC?) through 2-in diameter penetrations	6.28
	Open slit for conduit penetration for HVAC electrical?	40.00
	(16) 1/4-in diameter holes covered by 1-in covering (some type of tape)	3.14
	(2) 1-in diameter holes covered by 1.5-in covering (some type of tape)	1.57
Right Side	(2) plastic electrical wiring harness connections (4.75x2.5")	23.75
	1.5-in diameter hole with (3) 1/2-in diameter electrical cables (green)	1.77
	2-in connection with plastic conduit (electrical) centered on metal plate (2.75x6.5-in)	3.14
	1-in diameter hole with clear plastic tubing going through	0.79
	(2) 2.5x1.5-in oval holes - just open, nothing routed	2.95
	(2) 1.5-in pipe connections	3.53
	2-in diameter connection with conduit/hose running into pump at right side	3.14
	(3) blank 1-in diameter holes	2.36
	Steering connection - 5x2-in oval	7.85
	Blank 3/4-in connection located next to steering column	0.44
	(4) 1.5-in connections for plastic brake tubing (two 3/4-in diameter tubes and two 3/8-in diameter tubes)	7.07
	(3) 1/2-in connections covered with black grommet	0.59
	1/2-in connection with 1/4-in diameter black rubber tube penetration	0.20
	(4) 3/4-in diameter connections with tubing/covers/open	7.07
	3-in diameter opening with electrical conduit penetration	7.07
	(9) assorted bolt connections, 3/4-in diameter	3.98
	(4) assorted bolt connections, 1/2-in diameter	0.79
	Firewall Area (in^2):	1732.5
	Total Penetration Area (in^2):	127.47
	Total Penetration Fraction (%):	7.4
	Total Number of Penetrations:	62.0
	Average Penetration Area (in^2):	2.1

	Penetration No.	Penetration Description	Pentration Area (in^2)
Left Side	1	Two 1.5-in diameter hoses (HVAC?) through 2-in diameter penetrations	6.3
	2	Open slit for conduit penetration for HVAC electrical?	40.0
	3	(16) 1/4-in diameter holes covered by 1-in covering (some type of tape)	3.1
	4	(2) 1-in diameter holes covered by 1.5-in covering (some type of tape)	1.6
Right Side	5	(2) plastic electrical wiring harness connections (4.75x2.5")	23.8
	6	1.5-in diameter hole with (3) 1/2-in diameter electrical cables (green)	1.8
	7	2-in connection with plastic conduit (electrical) centered on metal plate (2.75x6.5-in)	3.1
	8	1-in diameter hole with clear plastic tubing going through	0.8
	9	(2) 2.5x1.5-in oval holes - just open, nothing routed	2.9
	10	(2) 1.5-in pipe connections	3.5
	11	2-in diameter connection with conduit/hose running into pump at right side	3.1
	12	(3) blank 1-in diameter holes	2.4
	13	Steering connection - 5x2-in oval	7.9
	14	Blank 3/4-in connection located next to steering column	0.4
	15	(4) 1.5-in connections for plastic brake tubing (two 3/4-in diameter tubes and two 3/8-in diameter tubes)	7.1
	16	(3) 1/2-in connections covered with black grommet	0.6
	17	1/2-in connection with 1/4-in diameter black rubber tube penetration	0.2
	18	(4) 3/4-in diameter connections with tubing/covers/open	7.1
	19	3-in diameter opening with electrical conduit penetration	7.1
	20	(9) assorted bolt connections, 3/4-in diameter	4.0
	21	(4) assorted bolt connections, 1/2-in diameter	0.8

Firewall Area (in^2):	1732.5
Total Penetration Area (in^2):	127.5
Total Penetration Fraction (%):	7.4
Total Number of Penetrations:	62.0
Average Penetration Area (in^2):	2.1



NS-IC- 2021 IC Full Length School Bus

Figure L-2. Schematic of penetrations for IC school bus at Navistar/IC Bus

Appendix M: Firewall Documentation of 2006 IC School Bus (Short)

Figure M-1 shows a photograph array of the IC (short bus) engine compartment surveyed at VRTC. Table M-1 provides a summary of the observed firewall penetration findings. Figure M-2 shows a schematic of the observed penetrations during the site visit.

Overall view

Firewall on right side

Firewall on left side

Firewall in center of engine compartment

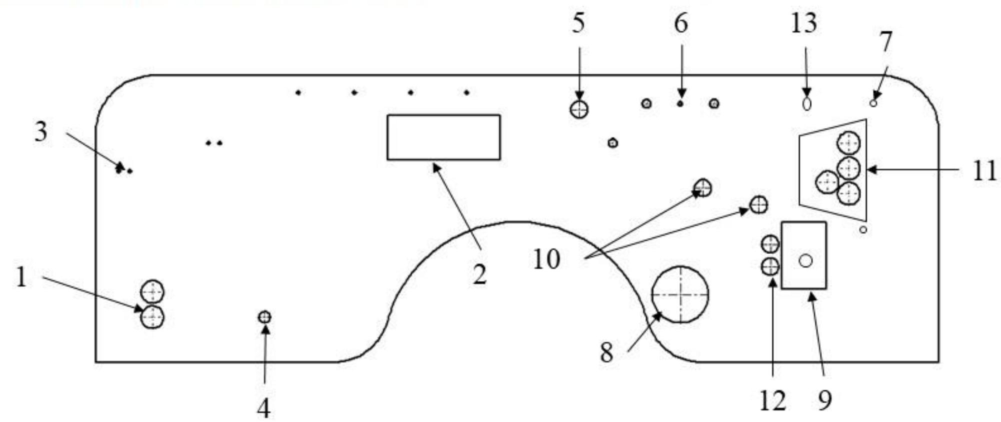
Figure M-1. Photograph array for IC bus (short) surveyed at VRTC

Table M-1. Summary of Penetrations for VRTC-IC Bus

	Penetration Description	Pentration Area (in^2)
Left Side	Two 2-in diameter penetrations but unused on this bus	1.57
	Open slit for conduit penetration for HVAC electrical (unused)	40.00
	(8) nominal 1/4-in holes (some covered with clear tape, others open)	0.39
	1-in diameter knockout with rubber cover - but unused	0.20
Right Side	Plastic conduit (~1/2" dia) in 1.5-in diameter penetration	1.77
	(1) 3/8" dia hole filled with bolt and (3) 3/4" dia holes filled with bolts	1.44
	(8) 1/4" diameter holes covered with tape or filled with bolt	0.39
	Steering column, nominal 5-in diameter penetration	19.63
	Brake assembly, nominal 4x6-in penetration cutout for mounting of brake component	24.00
	(2) 1.5-in dia holes covered with black rubber grommet	3.53
	Large cutout for wiring harnesses (4 nominal 2-in dia holes into PC - 3 used and one blank with rubber cov	12.57
	(2) nominal 1.5-in diameter hose penetrations	3.53
	Nominal 1.25-in diameter penetration with wiring connection	1.23
	Firewall Area (in^2):	1479
	Total Penetration Area (in^2):	110.25
	Total Penetration Fraction (%):	7.5
	Total Number of Penetrations:	33.0
	Average Penetration Area (in^2):	3.3

	Penetration No.	Penetration Description	Pentration Area (in^2)
Left Side	1	Two 2-in diameter penetrations but unused on this bus	1.57
	2	Open slit for conduit penetration for HVAC electrical (unused)	40.00
	3	(8) nominal 1/4-in holes (some covered with clear tape, others open)	0.39
	4	1-in diameter knockout with rubber cover - but unused	0.20
Right Side	5	Plastic conduit (~1/2" dia) in 1.5-in diameter penetration	1.77
	6	(1) 3/8" dia hole filled with bolt and (3) 3/4" dia holes filled with bolts	1.44
	7	(8) 1/4" diameter holes covered with tape or filled with bolt	0.39
	8	Steering column, nominal 5-in diameter penetration	19.63
	9	Brake assembly, nominal 4x6-in penetration cutout for mounting of brake component	24.00
	10	(2) 1.5-in dia holes covered with black rubber grommet	3.53
	11	Large cutout for wiring harnesses (4 nominal 2-in dia holes into PC - 3 used and one blank with rubber cover)	12.57
	12	(2) nominal 1.5-in diameter hose penetrations	3.53
	13	Nominal 1.25-in diameter penetration with wiring connection	1.23

Firewall Area (in2):	1479.0
Total Penetration Area (in2):	110.3
Total Penetration Fraction (%):	7.5
Total Number of Penetrations:	33.0
Average Penetration Area (in2):	3.3



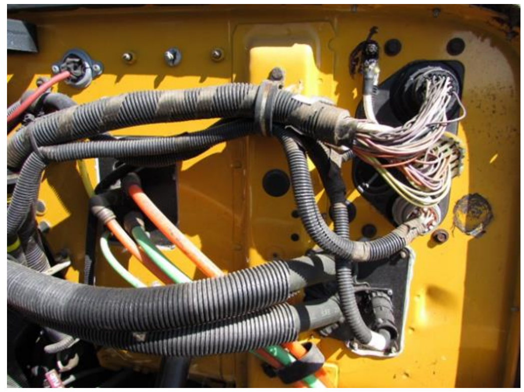
VRTC- 2006 IC School Bus (Short)

Figure M-2. Schematic of penetrations for IC bus (short) surveyed at VRTC

Appendix N: Firewall Documentation of 2004 IC School Bus (Long)

Figure N-1 shows a photograph array of the IC (long bus) engine compartment surveyed at VRTC. Table N-1 provides a summary of the observed firewall penetration findings. Figure N-2 shows a schematic of the observed penetrations during the site visit.

Overall view



Firewall on right side

Firewall on left side

Firewall on left side (close-up view)

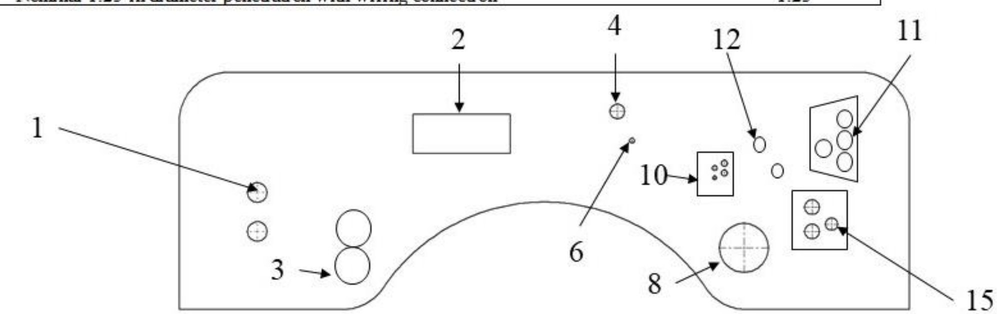
Figure N-1. Photograph array for IC bus (long) surveyed at VRTC

Table N-1. Summary of Penetrations for VRTC-IC Bus (Long)

	Penetration Description	Pentration Area (in^2)
Left Side	Two 1.5-in diameter hoses (HVAC?) through 2-in diameter penetrations	6.28
	Open slit for conduit penetration for HVAC electrical	40.00
	Custom cut hole in buikhead to allow conduit penetration (estimated as (2) 5-in dia holes)	39.27
Right Side	Red Wire (3/8" dia) in 1.5-in diameter penetration	1.77
	(2) 3/8" dia holes filled with bolt and (2) 1/2" dia holes filled with bolts	0.61
	Yellow hose (3/8" dia) in nominal 1/2" penetration bulkhead fitting connection	0.20
	3 nominal 1/2" holes (1 open hole and two covered with plastic grommet) under red wire	0.59
	Steering column, nominal 5-in diameter penetration	19.63
	(5) 1/2" dia holes filled with bolts - located close to steering penetration	0.98
	Brake assembly, nominal 4x6-in penetration cutout for mounting of brake component	24.00
	(4) 1/2" dia holes (2 covered with clear plastic grommett and two covered with black rubber grommett)	0.79
	(2) 1.5-in dia holes covered with black rubber grommet	3.53
	Large cutout for wiring harnesses (4 nominal 2-in dia holes into PC - 3 used and one blank with rubber cov	12.57
	(2) nominal 1.5-in diameter hose penetrations	3.53
	Nominal 1.25-in diameter penetration with wiring connection	1.23
	Firewall Area (in^2):	1467
	Total Penetration Area (in^2):	154.98
	Total Penetration Fraction (%):	10.6
	Total Number of Penetrations:	34.0
	Average Penetration Area (in^2):	4.6

	Penetration No.	Penetration Description	Pentration Area (in^2)
Left Side	1	Two 1.5-in diameter hoses (HVAC?) through 2-in diameter penetrations	6.28
	2	Open slit for conduit penetration for HVAC electrical	40.00
	3	Custom cut hole in bulkhead to allow conduit penetration (estimated as (2) 5-in dia holes)	39.27
Right Side	4	Red Wire (3/8" dia) in 1.5-in diameter penetration	1.77
	5	(2) 3/8" dia holes filled with bolt and (2) 1/2" dia holes filled with bolts	0.61
	6	Yellow hose (3/8" dia) in nominal 1/2" penetration bulkhead fitting connection	0.20
	7	3 nominal 1/2" holes (1 open hole and two covered with plastic grommet) under red wire	0.59
	8	Steering column, nominal 5-in diameter penetration	19.63
	9	(5) 1/2" dia holes filled with bolts - located close to steering penetration	0.98
	10	Brake assembly, nominal 4x6-in penetration cutout for mounting of brake component	24.00
	11	(4) 1/2" dia holes (2 covered with clear plastic grommett and two covered with black rubber grommett)	0.79
	12	(2) 1.5-in dia holes covered with black rubber grommet	3.53
	13	Large cutout for wiring harnesses (4 nominal 2-in dia holes into PC - 3 used and one blank with rubber cover)	12.57
	14	(2) nominal 1.5-in diameter hose penetrations	3.53
	15	Nominal 1.25-in diameter penetration with wiring connection	1.23

Firewall Area (in^2):	1467.0
Total Penetration Area (in^2):	155.0
Total Penetration Fraction (%):	10.6
Total Number of Penetrations:	34.0
Average Penetration Area (in^2):	4.6



VRTC- 2004 IC School Bus (Long)

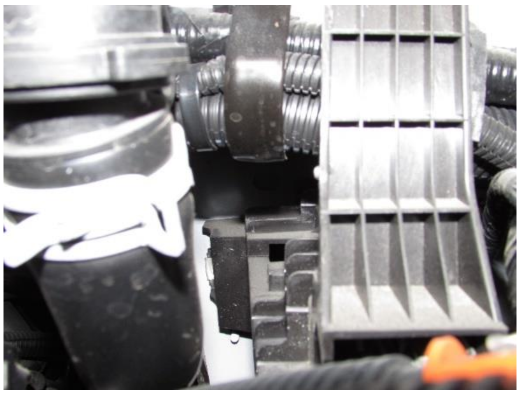
Figure N-2. Schematic of penetrations for IC bus (long) surveyed at VRTC

Appendix O: Firewall Documentation of 2021 Ford E-450 Paratransit Bus

Figure O-1 shows a photograph array of the Ford E-450 Super Duty/Starcraft Cutaway paratransit bus surveyed at the Tampa First Group facility.

Overall view of bus

Left side firewall view



Rght side firewall view

Interior view on driver's side

Figure O-1. Photograph array for Ford/Starcraft Cutaway Paratransit bus

Figure O-2 shows additional details for battery configuration and the engine cover. In general, this engine compartment was more congested than previously surveyed engine compartments and it was difficult to visually observe the firewall penetrations. The site visit hosts described this as well in that almost all engine maintenance required partial removal of the engine in order to access the areas in need. This congestion combined with the newest emission requirements leads to a higher operating temperature for these vehicles than earlier models.

The battery configuration is similar to both the Ford Paratransit van and also the GM/Champion Cutaway bus surveyed at the Brownsville, Texas, location, in terms of the battery compartment located on the passenger's side of the vehicle and also the distribution of cabling in the engine compartment.

The newly observed feature on this bus is the battery disconnect switch located under the driver's seat. This can be seen in the top right image of Figure O-2. The purpose of this switch is to disconnect power to the engine compartment, while keeping power in the passenger compartment for the purposes of egress. The site visit host is having these switches installed on all new buses that allow this option. Table O-1 shows a summary of the observed penetrations through the firewall. Figure O-3 shows a schematic of the penetrations.

View of Plastic engine cover

View of interior and battery disconnect switch on bottom of driver's seat

View of battery compartment on passenger side of vehicle

Battery distribution area in engine compartment (no battery)

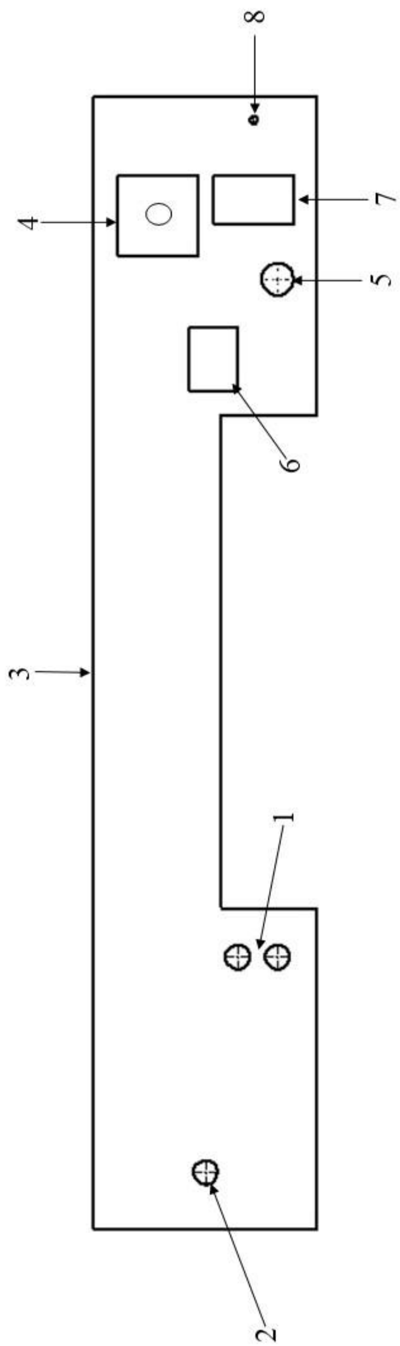
Figure O-2. Photograph array for Ford/Starcraft Cutaway Paratransit bus

Table O-1. Summary of Penetrations for Ford/Starcraft Cutaway Paratransit Bus

	Penetration Description	Pentration Area (in^2)
Left Side	(2) 1.5-in diameter connections for 3/4-in hoses - heater lines	3.53
	1.5-in diameter AC line	1.77
Center	Leakage around engine cover (nominal 6-ft perimeter length and 1/4-in gap)	18.00
Right Side	5x5-in plate connection for brake system	25.00
	2-in diameter steering connection	3.14
	4x3-in connection for wiring harnesses	12.00
	5x3-in plate connection behind coolant tank with 2-in diameter conduit/hose	15.00
	0.5-in hole for 0.25-in diameter tubing	0.20
	Firewall Area (in^2):	695
	Total Penetration Area (in^2):	78.64
	Total Penetration Fraction (%):	11.3
	Total Number of Penetrations:	9.0
	Average Penetration Area (in^2):	8.7

	Penetration No.	Penetration Description	Pentration Area (in^2)
Left Side	1	(2) 1.5-in diameter connections for 3/4-in hoses - heater lines	3.5
	2	1.5-in diameter AC line	1.8
Center	3	Leakage around engine cover (nominal 6-ft perimeter length and 1/4-in gap)	18.0
Right Side	4	5x5-in plate connection for brake system	25.0
	5	2-in diameter steering connection	3.1
	6	4x3-in connection for wiring harnesses	12.0
	7	5x3-in plate connection behind coolant tank with 2-in diameter conduit/hose	15.0
	8	0.5-in hole for 0.25-in diameter tubing	0.2

Firewall Area (in^2):	695.0
Total Penetration Area (in^2):	78.6
Total Penetration Fraction (%):	11.3
Total Number of Penetrations:	9.0
Average Penetration Area (in^2):	8.7



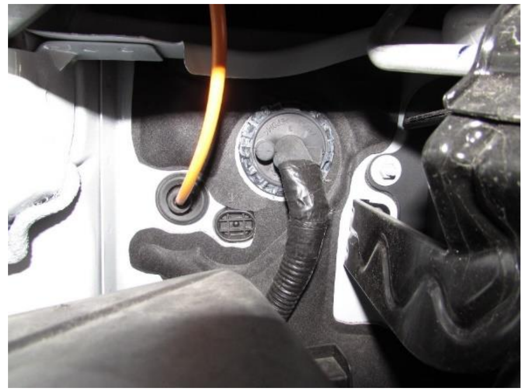
FG-TA 2021 Ford E-450 Para-Transit Bus

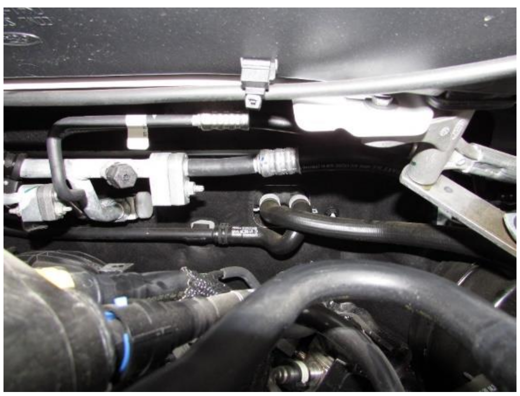
Figure O-3. Schematic of penetrations for Ford/Starcraft Cutaway Paratransit bus

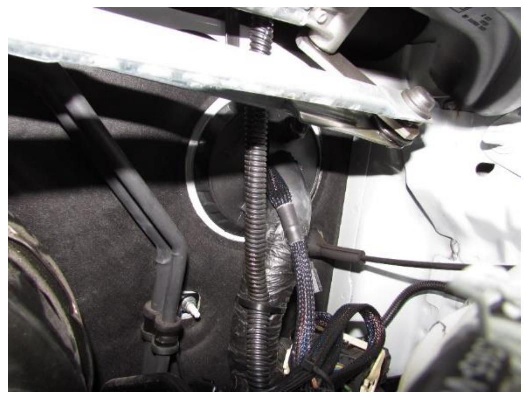
Appendix P: Firewall Documentation of 2021 Ford Cutaway Paratransit Van

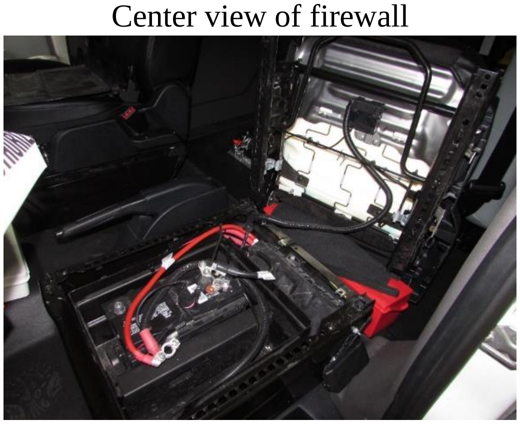
Figure P-1 shows a photograph array of the Ford Paratransit van engine compartment surveyed at the Tampa facility. The engine compartment for this van was very similar to the other medium-size buses surveyed at other sites. An interesting feature of this van design is the location of the battery, which is located under the driver's seat. In the engine compartment there is a distribution module for routing of these battery cables. The bottom two images in Figure P-1 shows the battery arrangement. Table P-1 shows a summary of the observed firewall penetrations.

Overall view of van


Left side firewall view


Center view of firewall


Rght side firewall view


Battery located under driver's seat


Battery cable terminal in engine compartment

Figure P-1. Photograph array for Ford Paratransit Van

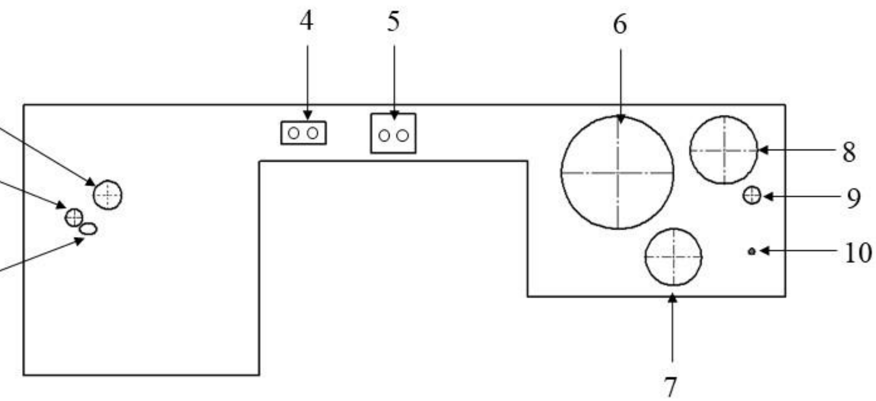
Table P-1. Summary of Penetrations for Ford Paratransit Van

	Penetration Description	Pentration Area (in^2)
Left Side	1.5-in diameter hole with 1/4-in orange tubing	1.77
	1.5 x 1-in oval opening, plugged with rubber stopper	1.18
	2.5-in diameter opening with electrical conduit	4.91
Center	4x2-in rectangular opening with AC connections (3/4-in and 3/8-in tubing)	8.00
	3.5x4-in rectangular opening with heater lines (3/4-in rubber hoses)	14
Right Side	10-in diameter connection including brake system	78.54
	5-in diameter steering connection	19.63
	6-in diameter connection with hose and braided line through rubber stopper	7.07
	Nominal 1.5-in diameter hole with 0.25-in diameter tubing	1.77
	Nominal 0.5-in diameter penetration with pipe penetration	0.20
	Firewall Area (in^2):	1135
	Total Penetration Area (in^2):	134.12
	Total Penetration Fraction (%):	11.8
	Total Number of Penetrations:	10.0
	Average Penetration Area (in^2):	13.4

Figure P-2 shows a schematic of the observed penetrations during the site visit.

	Penetration No.	Penetration Description	Pentration Area (in^2)
Left Side	1	1.5-in diameter hole with 1/4-in orange tubing	1.8
	2	1.5 x 1-in oval opening, plugged with rubber stopper	1.2
	3	2.5-in diameter opening with electrical conduit	4.9
Center	4	4x2-in rectangular opening with AC connections (3/4-in and 3/8-in tubing)	8.0
	5	3.5x4-in rectangular opening with heater lines (3/4-in rubber hoses)	14.0
Right Side	6	10-in diameter connection including brake system	78.5
	7	5-in diameter steering connection	19.6
	8	6-in diameter connection with hose and braided line through rubber stopper	7.1
	9	Nominal 1.5-in diameter hole with 0.25-in diameter tubing	1.8
	10	Nominal 0.5-in diameter penetration with pipe penetration	0.2

Firewall Area (in^2):	1135.0
Total Penetration Area (in^2):	134.1
Total Penetration Fraction (%):	11.8
Total Number of Penetrations:	10.0
Average Penetration Area (in^2):	13.4



FG-TA 2021 Ford Cutaway Para-Transit Van

Figure P-2. Schematic of penetrations for Ford Paratransit van

DOT HS 813 282
June 2022

U.S. Department
of Transportation

National Highway
Traffic Safety
Administration

NHTSA

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