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L. Robert Shelton,
Executive Director
NATIONAL HIGHWAY TRAFFIC
SAFETY ADMINISTRATION
400 Seventh Street, S.W., Room 5220
Washington, DC 20590

Dear Mr. Shelton:

Re: **Settlement Agreement**
Section B. Fire Safety Research

Enclosed is a paper prepared by H. S. Silvus and Robert E. White of Southwest Research Institute, entitled, "Inductances of Automotive Electromagnetic Devices."

This paper was presented at and published in the proceedings of the SAE 2002 World Congress held in Detroit, Michigan, March 4-7, 2002.

This paper relates to Sub-Project B.10 (c) (Evaluation of Spark Ignition of Flammable Air-Fuel Mixtures).

Yours truly,

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Inductances of Automotive Electromagnetic Devices

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Southwest Research Institute

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Inductances of Automotive Electromagnetic Devices

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ABSTRACT

A quantitative relationship between inductances and operating currents of automotive electromagnetic devices was necessary for experimentally assessing the nature of the spark that occurs when a current-carrying conductor in an automobile electrical system is broken. Various automotive electromagnetic devices were obtained, and their inductances and dc operating currents were measured. A plot of the data showed, as expected, that an inverse relationship existed, and regression analysis showed that the relationship could be expressed as

$$L = 8.62\, I^{-1.30}$$

where L is inductance in millihenries, and I is current in amperes. This formula, which provided sufficient accuracy for the intended experiments, may be used for estimating the inductance of an automotive electromagnetic device if the current drawn by the device is known.

INTRODUCTION

In automotive applications, many electrical loads (the notable exceptions being lamps) are inductive, so there is a relatively high probability that the load served by a randomly selected current-carrying conductor in a motor-vehicle electrical system will be inductive. Typical examples of inductive automotive loads are listed in Table 1 in Appendix A.

Because an inductor stores energy that must be dissipated when the current is interrupted and a resistor does not, the probability of spark generation is greater when an inductively loaded circuit is broken than when a resistively loaded circuit that carries the same current is broken.

In designing a series of experiments aimed at determining the current thresholds at which various fuel-air mixtures are ignited by the sparks generated when current-carrying automotive electrical circuits are either broken or repeatedly made and broken, it was noted that results would depend significantly on whether the test circuit included inductance. Thus, to facilitate determination of worst-case ignition thresholds, it was deemed necessary to include inductance in the test circuit. The question was: What inductance values should be used?

Obviously, magnetic structures of automotive electromagnetic devices vary widely, so it is expected that inductance values will vary widely also. However, even with the wide structural variation, it is reasonable to assume that inductance of a high-current device (e.g., a starter motor that has a few turns of large wire) will be lower than the inductance of a low-current device (e.g., a relay coil that has numerous turns of small wire). These observations suggest that there is an inverse, though probably noisy, relationship between inductance of an automotive electromagnetic device and the current that it draws. The reported work was intended to test these observations and to attempt to determine the coefficients of the relationship between inductances and operating currents of typical automotive electromagnetic devices.

QUALITATIVE ANALYSIS

As a starting point in determining the inductance-current relationship, an approximate qualitative analysis (Appendix B) of a highly simplified magnetic circuit was performed. This analysis showed that for the selected special configuration, there was an inverse relationship between inductance and current, namely,

$$L \propto I^{-0.5} \qquad (1)$$

where L is inductance in henries, and I is current in amperes.

In the selected configuration, several practically unrealistic assumptions were made to simplify analysis; for example, the core had a square cross section and no air gap. Further, physical dimensions of the magnetic circuit were in easily expressed proportions to the side of the square cross section; hence, core cross-sectional area, magnetic path length, and window dimensions, as well as mean length of a turn on the coil, were related to the side of the square core cross section. Additionally, wire gauge was related to current, and the number of turns was adjusted so that flux density in the core material was constant at a near-saturation value. Substitutions and combinations of the resulting equations facilitated expressing inductance as a function of current.

Because of the several simplifying assumptions, the analysis was admittedly imprecise; however, it did indicate the existence of an inverse relationship between inductance and current. Further, the analysis suggested that the relationship was of the power-law type.

DATA ACQUISITION

An easy way to determine the relationship between inductance and operating current would be to obtain the parameters of interest from specification sheets for a wide variety of automotive electromagnetic devices. However, because automotive electromagnetic devices are intended for direct-current (dc) service, inductance is usually not an important parameter; hence, drawings and specifications for such devices rarely include inductance values. Thus, the desired data were not readily available from specification sheets.

We obtained the necessary data by measuring inductances and dc operating currents or dc resistances of a variety of automotive electromagnetic devices made by a variety of manufacturers. Measured values were obtained from devices mounted on the experimenters' personal vehicles and from a number of automotive electromagnetic devices that were purchased from junkyards. The specific devices that were used and the associated operating-current and inductance values are listed in Table 2 in Appendix A.

Electromagnetic devices selected for the reported experiments ranged from light-duty relay coils to starter motors; operating current values spanned approximately three decades. Relay armatures were held in their pulled-in positions so that measured inductances represented the values that would exist when coil currents were interrupted. Motor inductance was monitored as the rotor was manually turned through 360 degrees, and the maximum value of inductance was recorded.

Currents drawn by relay coils and similar devices were computed from measured dc resistances and an assumed circuit voltage of 12 V using Ohm's law. Motors were operated under load, and currents were measured with a clip-on dc ammeter for on-vehicle devices or with the ammeter on the laboratory dc power supply used for off-vehicle testing.

Inductances were measured at a frequency of 100 Hz using a Hewlett Packard 4263B LCR meter, and dc resistances were measured with a Keithley 191 digital multimeter. Both of these instruments provide four-terminal Kelvin connections that eliminate test-lead parameters from the measured values.

DATA ANALYSIS

Figure 1 is a graph of the various measured inductance-current pairs. A curve-fitting program (TableCurve 2D®) was used to determine a formula that described the best-fit relationship between the measured values of inductance and corresponding current values; the best-fit function is also plotted in Figure 1.

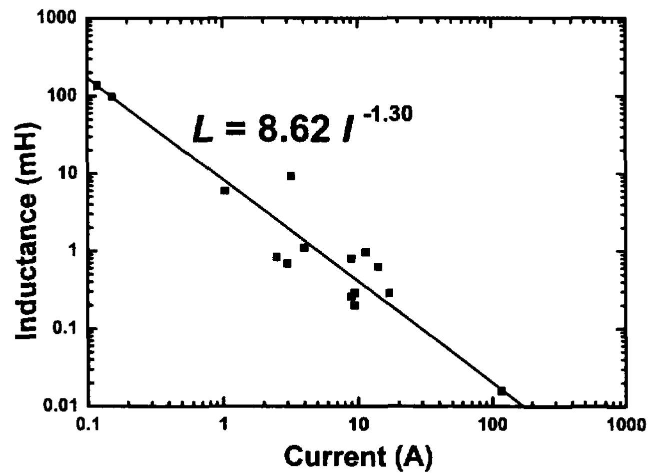

Figure 1. Inductance versus current for typical automotive electromagnetic devices

Even without the best-fit curve, it is evident that there is an inverse trend in the data and that the trend is somewhat noisy as expected. However, addition of the best-fit curve shows that there is an amazingly consistent relationship between inductance and device operating current. Specifically, the best-fit relationship may be expressed as

$$L = 8.62\, I^{-1.30} \qquad (2)$$

where L is inductance in millihenries, and I is current in amperes.

Except for three outliers, measured inductance values were within ±69% of values calculated using equation (2). The three outliers were approximately 128%, 163%, and 386% of the respective calculated values.

CONCLUSIONS

For typical automotive electromagnetic devices, an inductance-versus-current trend exists, and most of the measured values obtained from a wide range of such devices were grouped about the power-law relationship

$$L = 8.62\, I^{-1.30}$$

where ***L*** is inductance in millihenries, and ***I*** is current in amperes.

ACKNOWLEDGEMENTS

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APPENDIX A - TABLES

TABLE 1. REPRESENTATIVE INDUCTIVE LOADS IN AUTOMOTIVE ELECTRICAL SYSTEMS

Active-suspension solenoids	Relay coils (e.g., for radiator-fan motor, horn, headlights, heating/air-conditioning blower motor and high-speed control, air-conditioning-compressor clutch, rear-window defogger, cruise control, etc.)
Air-conditioning-compressor clutch	Starter motor
Anti-lock-braking solenoids	Starter solenoid
Automatic-transmission control solenoids	Trunk-release solenoid
Door-lock solenoids	Window and sunroof motors
Electric-seat motor	Windshield-washer pump motor
Fuel-injector solenoid	Windshield-wiper motor
Heating/air-conditioning blower motor	
Horn	
Ignition-coil primary	
Radiator-fan motor	

TABLE 2. MEASURED INDUCTANCES AND OPERATING CURRENTS OF TYPICAL AUTOMOTIVE ELECTROMAGNETIC DEVICES

Device	Measured Current (A)	Measured Inductance (mH)	Calculated Inductance (mH)	(Meas.-Calc.)/Calc. (%)
Small-relay coil	0.119	135.0	137.2	-1.59
Small-relay coil	0.119	138.6	137.2	1.03
Large-relay coil	0.154	98.70	98.11	0.60
Fuel injector	1.035	6.014	8.243	-27.04
Windshield-wiper motor (Low speed)	2.500	0.835	2.619	-68.12
Windshield-washer pump motor	3.000	0.687	2.067	-66.76
Air-conditioning compressor-clutch coil	3.183	9.303	1.913	386.19
Windshield-wiper motor (High speed)	4.00	1.104	1.422	-22.35
Fuel-pump motor	9.00	0.800	0.4954	61.47
Fuel-pump motor	9.00	0.260	0.4954	-47.52
Radiator-fan motor	9.50	0.290	0.4618	-37.20
Fuel-pump motor	9.50	0.200	0.4618	-56.69
Horn	11.39	0.960	0.3648	163.18
Starter solenoid	14.17	0.627	0.2746	128.32
Air-conditioning/heater fan motor	17.0	0.255	0.2167	17.66
Starter motor	117	0.0159	0.01765	-9.94

APPENDIX B – APPROXIMATE ANALYSIS OF SIMPLIFIED MAGNETIC CIRCUIT

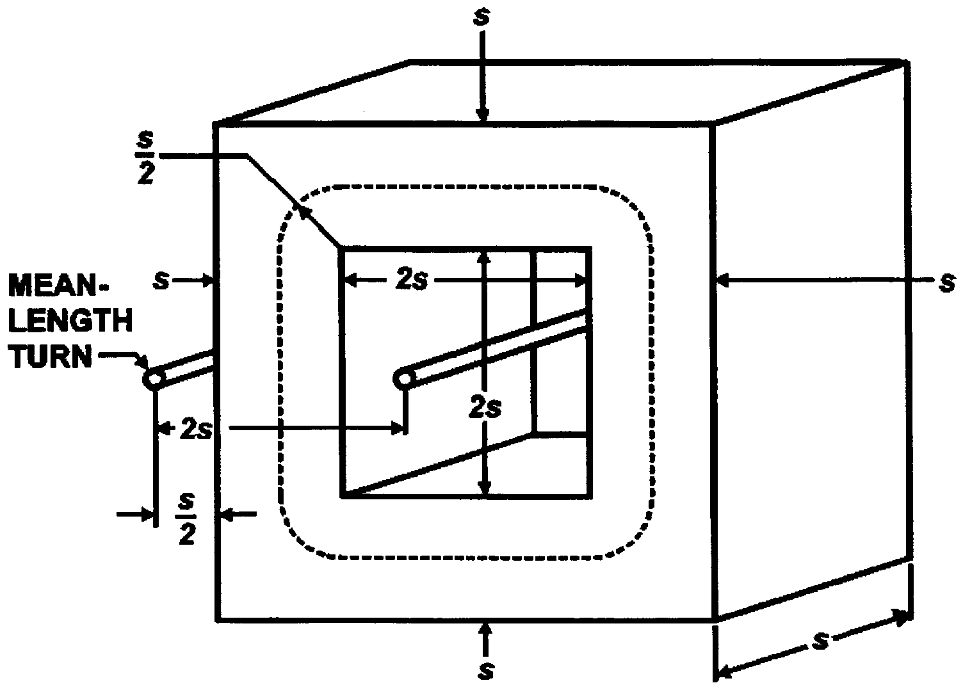

Figure B1. Assumed magnetic-circuit configuration

Definitions of variables:

A	=	Cross-sectional area of core (m^2)
B	=	Magnetic-flux density in core (T)
B_{MAX}	=	Saturation magnetic-flux density of core material (T)
d	=	Diameter of coil wire (m)
H	=	Magnetic-field intensity (A/m)
I	=	Coil current (A)
k	=	Ratio of square of wire diameter to current rating of wire (m^2/A)
L	=	Inductance of coil (H)
ℓ_C	=	Effective magnetic path length of core (m)
ℓ_T	=	Mean length of coil turn (m)
N	=	Number of turns on coil
R	=	Coil resistance (Ω)
s	=	Side of core square cross section (m)

V = Voltage impressed across coil terminals (V)

Φ = Magnetic flux in core (Wb)

μ = Effective relative permeability of core material

μ_0 = Permeability of free space (H/m)

ρ = Resistivity of coil wire material (Ω•m)

Derivation:

Area of square cross section of core:

$A = s^2$ (B1)

Solving equation (B1) for s:

$$s = \sqrt{A} \tag{B2}$$

Magnetic path length of core with substitution of equation (B2):

$$\ell_C = 8s + 2\pi\left(\frac{s}{2}\right) = (8+\pi)\sqrt{A} \tag{B3}$$

Mean length of coil turn with substitution of equation (B2):

$$\ell_T = 4s + 2\pi\left(\frac{s}{2}\right) = (4+\pi)\sqrt{A} \tag{B4}$$

Relationship between wire diameter and current-carrying capacity:

$d^2 = kI$ (k = 2.23 x 10^{-7} m^2/A based on National Electrical Code rating of 30 A for #10 AWG copper wire) (B5)

Resistance of coil with substitution of equations (B4) and (B5):

$$R = \frac{N\rho\,\ell_T}{\left(\frac{\pi d^2}{4}\right)} = \frac{4(4+\pi)\rho N\sqrt{A}}{\pi k I} \tag{B6}$$

Voltage dropped across coil resistance (i.e., equation (B6) multiplied by I):

$$V = IR = \frac{4(4+\pi)\rho N\sqrt{A}}{\pi k} \tag{B7}$$

Rearranging equation (B7):

$$N\sqrt{A} = \frac{\pi kV}{4(4+\pi)\rho} \tag{B8}$$

Magnetic-field intensity:

$$H = \frac{NI}{\ell_C} \tag{B9}$$

Magnetic-flux density in core material:

$$B = \mu \mu_0 H \tag{B10}$$

Total magnetic flux in core with substitutions of equations (B10), (B9), (B3), and (B8):

$$\Phi = BA = \mu \mu_0 HA = \frac{\mu \mu_0 NIA}{\ell_C} = \frac{\mu \mu_0 NIA}{(8+\pi)\sqrt{A}} = \frac{\mu \mu_0 I}{8+\pi} \cdot N\sqrt{A} = \frac{\mu \mu_0 I}{8+\pi} \cdot \frac{\pi k V}{4(4+\pi)\rho} \tag{B11}$$

Saturation magnetic-flux density in core material with substitution of equation (B3):

$$B_{MAX} = \frac{\mu \mu_0 NI}{\ell_C} = \frac{\mu \mu_0 NI}{(8+\pi)\sqrt{A}} \tag{B12}$$

Rearranging equation (B12):

$$\frac{N}{\sqrt{A}} = \frac{(8+\pi)B_{MAX}}{\mu \mu_0 I} \tag{B13}$$

Multiplying equation (B8) by equation (B13):

$$N\sqrt{A}\left(\frac{N}{\sqrt{A}}\right) = N^2 = \frac{(8+\pi)B_{MAX}}{\mu \mu_0 I} \cdot \frac{\pi k V}{4(4+\pi)\rho} \tag{B14}$$

Solving equation (B14) for N:

$$N = \sqrt{\frac{\pi(8+\pi)kVB_{MAX}}{4(4+\pi)\mu \mu_0 \rho I}} \tag{B15}$$

Applying definition of inductance, substituting equations (B15) and (B11), grouping terms, and evaluating derivative:

$$L = \frac{d}{dI}(N\Phi) = \frac{d}{dI}\left[\sqrt{\frac{\pi(8+\pi)kVB_{MAX}}{4(4+\pi)\mu \mu_0 \rho I}} \cdot \frac{\mu \mu_0 I}{8+\pi} \cdot \frac{\pi k V}{4(4+\pi)\rho}\right]$$

$$= \frac{d}{dI}\left[\sqrt{\left(\frac{\pi k V}{4(4+\pi)\rho}\right)^3 \left(\frac{\mu \mu_0 B_{MAX}}{8+\pi}\right)}\sqrt{I}\right] = \frac{1}{2}\sqrt{\left(\frac{\pi k V}{4(4+\pi)\rho}\right)^3 \left(\frac{\mu \mu_0 B_{MAX}}{8+\pi}\right)}\frac{1}{\sqrt{I}} \tag{B16}$$

Key result:

$$L \propto \frac{1}{\sqrt{I}} = I^{-0.5} \quad \text{(For the selected special configuration only)} \tag{B17}$$