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16. Abstract

Reducing congestion in our nation's urban areas has become a top priority nationwide for state departments of transportation. The recent development and construction of freeway management systems have begun to help reduce these problems. A major component of freeway management systems is the inductance loop detector. This research effort evaluated the use of inductance loop detectors in a freeway management situation to determine maximum permissible lead lengths.

Using several detector units, researchers evaluated lead lengths with five different design vehicles (large and small passenger cars, a pickup truck, a motorcycle, and a high profile truck). Both passenger cars and the pickup truck were always detected with 1,220 meters (4,000 feet) of lead wire on all combinations of sensitivity level and number of wire turns. The detection of the motorcycle and high profile truck depended upon the sensitivity level and number of wire turns used. The data also indicate that detection of the passenger vehicles may be possible at distances much greater than 1,220 meters (4,000 feet). An extrapolation of the inductance measurements indicates that detection of passenger vehicles at 2,440 meters (8,000 feet) is likely, and detections may even be possible at much larger distances. Lead lengths of this magnitude give the designer greater flexibility in producing the most functional and cost-effective design.

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INDUCTANCE LOOP DETECTOR LEAD LENGTH

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IMPLEMENTATION STATEMENT

This research provides a better understanding of detector lead length limits which allows more effective use of induction loop detectors by the Texas Department of Transportation and local governmental units in Texas. With the increasing development of freeway management systems, this research will provide the designer with practical information as to the maximum lead length permissible for accurate detection.

DISCLAIMER

The contents of this report reflect the views of the authors who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official view or policies of the Texas Department of Transportation, or the Federal Highway Administration. This report does not constitute a standard, specification, or regulation, nor is it intended for construction, bidding, or permit purposes. Dr. Donald L. Woods (P.E. # 21315) was the Principal Investigator for the project.

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SUMMARY

Reducing congestion in our nation's urban areas has become a top priority nationwide for state departments of transportation. The recent development and construction of freeway management systems have begun to help reduce these problems. A major component of freeway management systems is the inductance loop detector. This research effort evaluated the use of inductance loop detectors in a freeway management situation to determine maximum permissible lead lengths.

Using several detector units, researchers evaluated lead lengths with five different design vehicles (large and small passenger cars, a pickup truck, a motorcycle, and a high profile truck). Both passenger cars and the pickup truck were always detected with 1,220 meters (4,000 feet) of lead wire on all combinations of sensitivity level and number of wire turns. The detection of the motorcycle and high profile truck depended upon the sensitivity level and number of wire turns used. The data also indicate that detection of the passenger vehicles may be possible at distances much greater than 1,220 meters (4,000 feet). An extrapolation of the inductance measurements indicates that detection of passenger vehicles at 2,440 meters (8,000 feet) is likely, and detections may even be possible at much larger distances. Lead lengths of this magnitude give the designer greater flexibility in producing the most functional and cost-effective design.

1.0 INTRODUCTION

Traffic congestion in the United States has been increasing at an alarming rate for many years. In an effort to combat this problem, many transportation agencies are implementing traffic monitoring programs or traffic management centers. Typically, these programs involve automated systems that measure traffic flow characteristics such as lane volume, occupancy, and average speed. The main component of virtually all programs in the United States is the inductance loop detector (ILD). ILDs are relatively inexpensive traffic detectors which have the capability of measuring and recording traffic characteristics.

The loop itself consists of a standard electrical wire embedded in the pavement surface in a variety of shapes, most commonly a 1.8 meter (6 foot) square. A detector unit housed in a control cabinet near the roadway sends an electrical current through the wire, which creates an electromagnetic field. As vehicles travel over the loop, energy is removed from the system by the vehicle causing a change in the tuned radio frequency (RF) circuit. The detector unit senses this change in frequency and, if sufficiently large, detects the vehicle. The low cost of the components of ILDs has helped to make the ILD the most widely used vehicle detector today.

1.1 PROBLEM STATEMENT

The freeway environment in which the ILDs must now operate introduces a new factor not present at signalized intersections, namely, longer loop detector lead lengths. The loop detector lead length is the length of the wire from the loop itself to the control cabinet. At signalized intersections, the lead lengths are typically less than 60 meters (200 feet). However, in the freeway environment, lead lengths may approach 800 meters (2,600 feet). Therefore, it is desirable to determine the maximum lead length that is possible for effective ILD operation.

1.2 OBJECTIVES/SCOPE

The primary objective of this study was to experimentally determine the maximum allowable lead length possible for effective ILD operation. The scope of this research was limited to evaluating lead lengths up to 1,220 meters (4,000 feet). All data were collected in a controlled environment at the Texas A&M University Riverside Campus. The near perfect testing environment allowed for very long lead lengths. While this is possible, long lead lengths are not recommended for general use.

1.3 ANTICIPATED BENEFITS

This research provides a better understanding of detector lead length limits which allows more effective use of induction loop detectors by the Texas Department of Transportation and local governmental units in Texas. With the increasing development of freeway management systems, this research will provide the designer with practical information as to the maximum lead length permissible for accurate detection.

2.0 BACKGROUND

Induction Loop Detectors have been used for many years in the operation of traffic signals. Therefore, much of the available literature concerns the placement and installation of ILDs for the specific purpose of operating signalized intersections more efficiently. For use in a freeway management system, the operation of ILDs with long lead lengths is not well documented. The background and literature review completed for this research effort concentrated on inductance loop lead length requirements.

2.1 INDUCTANCE LOOP DETECTOR PROPERTIES

An inductance loop detector is composed of a standard electrical wire embedded in the pavement surface. The Electronic Engineers and Technicians Reference Handbook defines *inductance* as "the property of a circuit element which tends to oppose any change in current through it" (1, p.123). The wire's perimeter, width, the effective radius of its cross-section, the number of turns, and the permeability of the medium around the wire govern its inductance. When this wire is buried in a stable road surface, all of the above properties are constant causing the loop to have a stable inductance. Alternating current is passed through the wire, typically by the detector unit (or amplifier), creating an electromagnetic field around the loop. Should a vehicle or an object containing a closed loop of electrically conductive material enter this field, the energy of the system will be reduced, causing the inductance of the loop to decrease. This changes the frequency of the RF circuit, and if sufficiently large is detected by the detector unit (2).

The inductance of the loop is affected by a variety of factors including weather, condition of the wire, and type of wire. However, the changes in inductance caused by these factors occur slowly over time and generally do not affect the operation of the loop. Many professionals believe that water also adversely affects loop operations. However, a recent study determined that water does not have a large impact on inductance loop operation (3). The inductance of the loop itself is affected by the water, but the detector units in use today can adjust to the new inductance and accurately detect vehicles. Provided the wire is insulated and uncut, water does not have a large impact on the operation of inductance loop detectors.

A factor which evaluates the efficiency of a circuit is the "Q" or quality factor (a dimensionless index). If the losses in the system are large, the Q value will be low. Likewise, if there are few losses in the loop system, the Q value will be large, typically between 30 and 40. Q is defined as (4):

$$Q = \frac{2 \pi f L_s}{R_s} = \frac{\omega L_s}{R_s}$$

Where: Q = Quality factor
π = 3.14159
f = Series inductance frequency, Hz.
L_S = Series inductance, henries
R_S = Resistance, ohms
$\omega = 2 \pi f$

The Q factor is complicated by the fact that the actual resistance of the loop wire and lead-in cable is larger than the actual series value. These losses are due to the high frequency of operation and ground currents in the pavement associated with the environment of the roadway surrounding the wire. Therefore, Q will vary from location to location, with an acceptable Q value in common practice usually being greater than 20.

2.2 THE EFFECTS OF LEAD LENGTH

The Federal Highway Administration Traffic Detector Handbook (4) does not identify the maximum lead length for the accurate detection of vehicles. However, Table 7 in the handbook does illustrate the effect of lead length on the Q value of the loop system. The table includes lead lengths up to 305 meters (1,000 feet), at which point the Q value of the loop system drops to 5. A Q value of 5 indicates that the loop is in poor condition and many losses exist in the system. Therefore, it is assumed that the authors of the handbook do not recommend using a lead length greater than 305 meters (1,000 feet).

A preliminary study completed during the summer of 1993 (5) used an inductor box in series with the loop detection system to simulate long lead lengths. Each 30 meters (100 feet) of lead wire added to the system added 23 microhenries of inductance. Therefore, by using the inductor box and adding microhenries of inductance to the system, operating conditions with longer lead lengths were approximated. The study determined that lead lengths of between 915 and 2,622 meters (3,000 and 8,600 feet) were possible, depending on the type of detector unit in the system. This study verified these results using up to 1,220 meters (4,000 feet) of actual lead wire instead of the inductor box simulation.

3.0 STUDY DESIGN

This research consisted of several distinct tasks. This chapter provides a discussion of the major activities and issues associated with each task. The research for this study was conducted in a controlled environment at the Texas Transportation Institute testing area located at the Texas A&M University Riverside Campus.

3.1 CONSTRUCTING THE TESTING AREA

The testing area consisted of four 1.8 meter by 1.8 meter (six foot by six foot) inductance loop detectors installed on a concrete runway. The ILDs were located 5 meters (15 feet) from the edge of the pavement in the center of a 3.8 meter (12.5 foot) wide panel, as shown in Figure 1. The loop itself was cut into the concrete pavement. All the sawcuts were 50 mm (2 inches) deep, with the width of the cut varying from 6.25 mm (1/4 inch) to 12.5 mm (1/2 inch) depending on the type of wire used. The loops were spaced 6, 15, and 24 meters (20, 50, and 80 feet) apart measured from the front edge of Loop A to the front edge of each successive loop. From the edge of the pavement, the loop wire ran underground through a 25 mm (1 inch) diameter PVC pipe to the pullbox.

The composition of loops A, B, and C consisted of #12 THHN wire while Loop D consisted of 6 conductors of #18 AWG, 3 pair, AWM style 2464, 300V, 80° C, unshielded cable. The first three loops were constructed with 3 complete turns and 3 individual turns all coming out to the pull box. This allowed for each loop to be tested with 3, 4, 5, and 6 turns of wire. Loop D was constructed similarly, except that the three turn loop was connected in the pull box since the wire was 6 conductor unshielded. Permanent Sealer 974 sealed the loops permanently into the saw cuts.

3.2 EVALUATION OF LEAD LENGTH

The lead length study utilized loop detector A and lead lengths of 0, 305, 610, 915, and 1,220 meters (0, 1,000, 2,000, 3,000, and 4,000 feet). The actual total length of wire was 1,205 meters (3,952 feet), but for ease of discussion, this length will be referred to as 1,220 meters (4,000 feet). Researchers constructed the lead lengths using a continuous line of two conductor #14 shielded wire. The 1,220 meter (4,000 foot) lead length testing was completed first and then cut down to smaller lead lengths for the remainder of the testing. The 1,220 meters (4,000 feet) of lead wire was placed along side the runway as indicated in Figure 2, and the detector units were connected to the end of the lead wire. The drivers of the vehicles and the data collector at the end of the lead communicated using hand held radios.

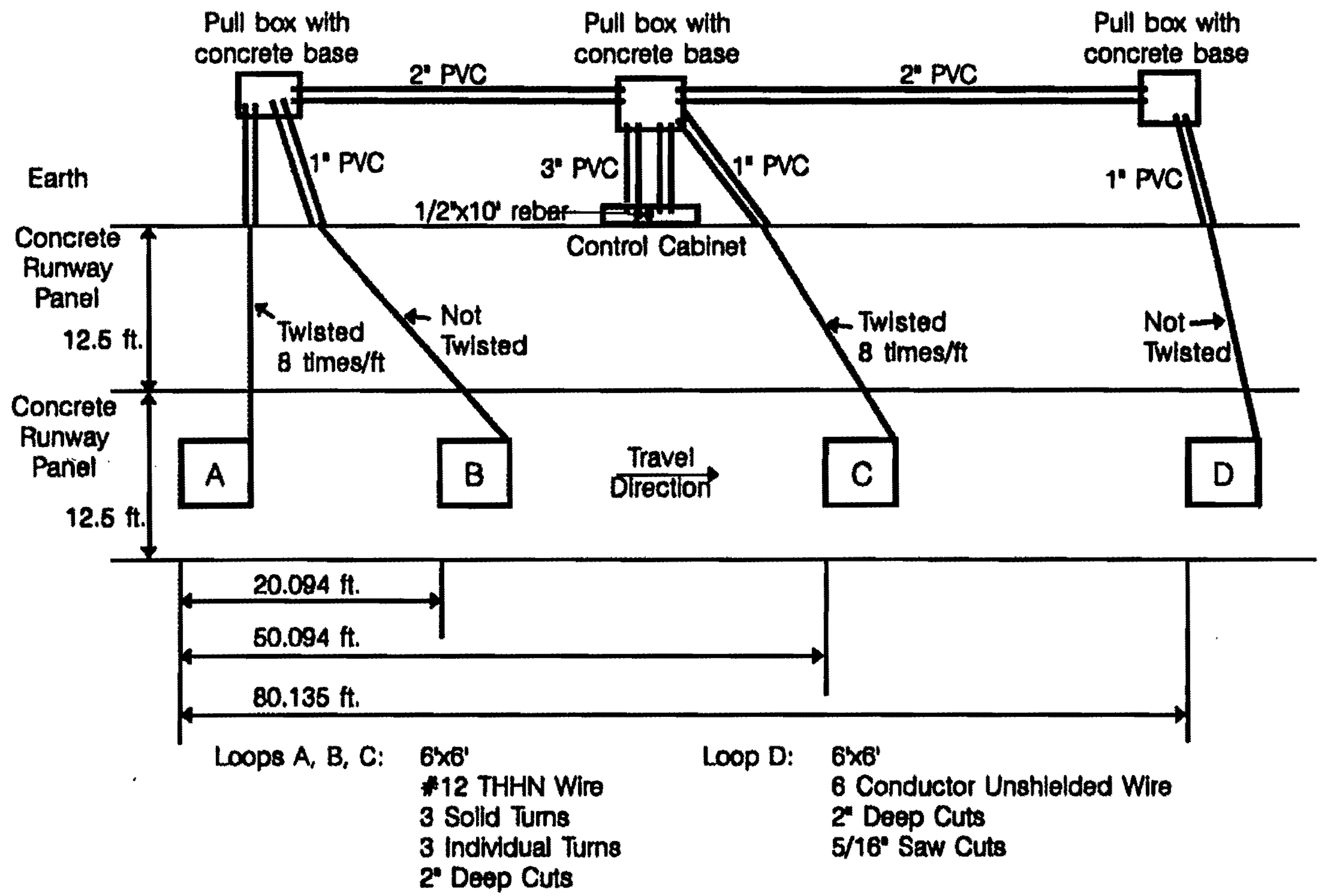

Figure 1. Site Layout

Note: 1 foot = .3048 meters and 1 inch = 2.54 centimeters

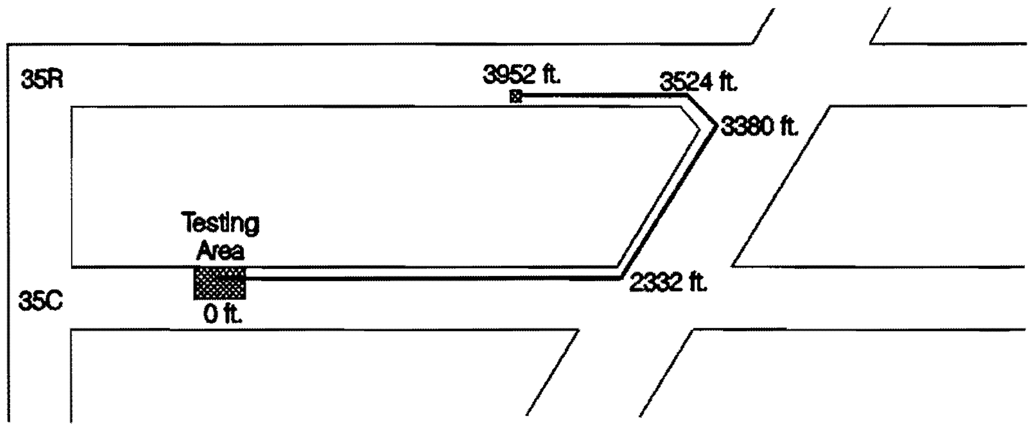

Figure 2. Placement of the Lead Wire Along Runway 35C at the Test Site
Note: 1 foot = .3048 meters

Three different detector units were tested with five design vehicles (a large car, a small car, a pickup truck, a motorcycle, and a high profile truck) as identified in Table 1. More detailed dimensions for the motorcycle and high profile truck can be found in Appendix A. Each vehicle made five passes over the loop at 32, 65, 97, and 129 km/h (20, 40, 60, and 80 miles per hour). The motorcycle and high profile truck failed to reach 129 km/h (80 mph), so testing was discontinued at 97 km/h (60 mph). Each detector was tested in the presence mode of operation, so an accurate detection required the detector unit to hold the call while the vehicle was within the loop. This definition became especially important during the testing of the high profile truck since the detectors have the tendency to detect the truck as two vehicles instead of one.

A frequency meter measured the frequency of the loop system, which includes the loop wire, lead wire, and detector unit. The same frequency meter then measured the frequency of the loop system while each of the design vehicles was parked on the loop. The frequency measurements were then converted to an inductance in order to determine the percent change in frequency caused by each of the design vehicles. Researchers measured and calculated all combinations of wire turns and lead length for each vehicle.

The entire test series was conducted four times for each lead length using 3, 4, 5, and 6 turns of wire beginning with 1,220 m (4,000 feet) of lead. After researchers obtained 100% accurate detections at a particular lead length with a certain vehicle, that lead length and number of wire turns was not tested further. This decision was made because of the fact that if accurate detections occurred at 1,220 m (4,000 feet), accurate detections would also be accomplished at shorter lead lengths. Completion of this series of tests determined the maximum lead length that can be successfully used for accurate vehicle detection in a freeway management system.

Table 1. Classification of Design Vehicles

Classification	Vehicle	Height Above Pavement	Vehicle Length	Front Vehicle Width
Small Car	1987 Honda Civic	225 mm (9")	3.9 m (12'10")	1.6 m (5'1")
Large Car	1991 Ford Crown Vict.	213 mm (8.5")	5.3 m (17'3")	1.9 m (6'3")
Pickup Truck	1988 Chevy S-10 Longbed	225 mm (9")	5.1 m (16'9")	1.6 m (5'4")
Motorcycle	1982 Suzuki 3006SL	184 mm (7.25")	2.1 m (6'9")	0.5 m (1'6")
High Profile Truck	Kenworth Tractor-Trailer	1,263 mm (50.5")	16.5 m (54'2")	2.4 m (8'0")

4.0 LEAD LENGTH STUDY RESULTS

Longer lead lengths will give the designer and transportation engineer more flexibility in the design and construction of an efficient traffic management system. This portion of the study identified the maximum lead lengths possible to effectively detect five design vehicles at speeds that are typical of modern freeway traffic.

4.1 DETECTION OF PASSENGER CARS

The large car, small car, and pickup truck used in the study were always detected at 1,220 meters (4,000 feet) with three, four, five and six turns of wire on low, medium and high sensitivity with all three models of detector units. All detections were in the presence mode of operation at speeds of 32, 64, 97, and 129 km/h (20, 40, 60, and 80 mph). The measurement of the percent change in inductance completed for each vehicle yielded changes of over 0.5% for three turns of wire and over 1.7% for 6 turns of wire. For a detection to occur, the percent change in inductance for the three models of detector units used in this study must be, on average, at least 0.2% for low sensitivity, 0.05% for medium sensitivity and 0.02% for high sensitivity. At a lead length of 1,220 meters (4,000 feet), the percent change for the three passenger vehicles was greater than 0.5% on three turns of wire, so detection at lead lengths much greater than 1,220 meters (4,000 feet) is possible. Complete data tables for the results of each vehicle and lead length can be found in Appendix B.

Since longer lead lengths are possible, it became desirable to estimate the maximum lead length that can be used in a freeway situation. Researchers measured the frequency change caused by each vehicle at 0, 305, 610, 915, and 1,220 meters (0, 1,000, 2,000, 3,000, and 4,000 feet) of lead using a frequency meter. The frequency was then converted to an inductance and the percent change in inductance could be calculated, as described in Section 3.2. A plot of the resulting data indicated that the relationship between the percent change in inductance and lead length is not linear. The relationship appeared to be either log-log, normal-log, or log-normal. Equations for all three relationships were developed using simple linear regression in ABSTAT, a statistical analysis software package. The majority of the best models were for a log-log distribution, with a few best fit models being normal-log distributions. Therefore, resulting best fit equations for all vehicles were determined using the log-log distribution and simple linear regression. Table 2 lists the R^2 values for each regression model. Figures 3, 4, and 5 illustrate the resulting models for the large car, small car, and pickup truck. Appendix C includes the regression data for all vehicles.

Table 2. Coefficients of Determination for the Linear Regression Models for the Large Car, Small Car, and Pickup Truck

Number of Wire Turns	Large Car	Small Car	Pickup Truck
3	0.9945	0.9897	0.9897
4	0.9997	0.9907	0.9907
5	0.9760	0.9787	0.9787
6	0.9961	0.9959	0.9959

By plotting the best fit models, the maximum allowable lead length for each vehicle, number of wire turns, and sensitivity level could be approximated. The figures identify the estimated maximum lead lengths for the three passenger vehicles tested based only on the regression models. The data clearly indicate that accurate detection of passenger vehicles with a lead length beyond 1,220 meters (4,000 feet) is possible. The extent beyond 1,220 meters (4,000 feet) that detection is possible is still unknown. However, the extrapolation of the data indicate that it may be possible to detect vehicles with long lead lengths that are beyond the current scope of practicality. The cost of wire alone for lead lengths becomes a significant factor where lengths exceed one mile. Due to the variable nature of data extrapolation procedures, the estimated maximum lead length values are not considered to be reliable. However, the shapes of the extrapolated curves take the same form as the effect of lead length versus loop inductance. The industry standard for lead wire adds 23 microhenries of inductance to the system for every 30.5 meters (100 feet) of lead wire. Therefore, every 305 meters (1000 feet) of lead wire adds 230 microhenries of inductance to the system. Since the vehicle is only interacting with the loop itself, the ratio of loop inductance to the total inductance in the loop system (loop plus lead length) should be similar to the percent change in inductance caused by a vehicle. Assuming a loop operating with a base inductance of 200 microhenries, Figure 6 indicates the effect of that lead length on the loop inductance ratio described above. This figure depicts the ratio of the loop inductance to the loop system inductance as the lead length increases. Note that the inductance ratio is negatively exponentially distributed and begins to stabilize for lead lengths beyond 1,220 meters (4,000 feet). Likewise, the change in inductance created by a vehicle over that loop will begin to stabilize, as shown in the extrapolation of the curves in Figures 3, 4, and 5. Thus, based on this theoretical relationship longer lead lengths are completely within the realm of possibility for the detection of passenger cars.

Even though extremely large lead lengths may be possible with passenger cars, odd-sized vehicles are the limiting factor to consider when choosing an appropriate inductance loop design because of the difficulties typically inherent with accurately detecting them. Without the detection of odd-sized vehicles, the maximum lead length possible for passenger cars becomes meaningless.

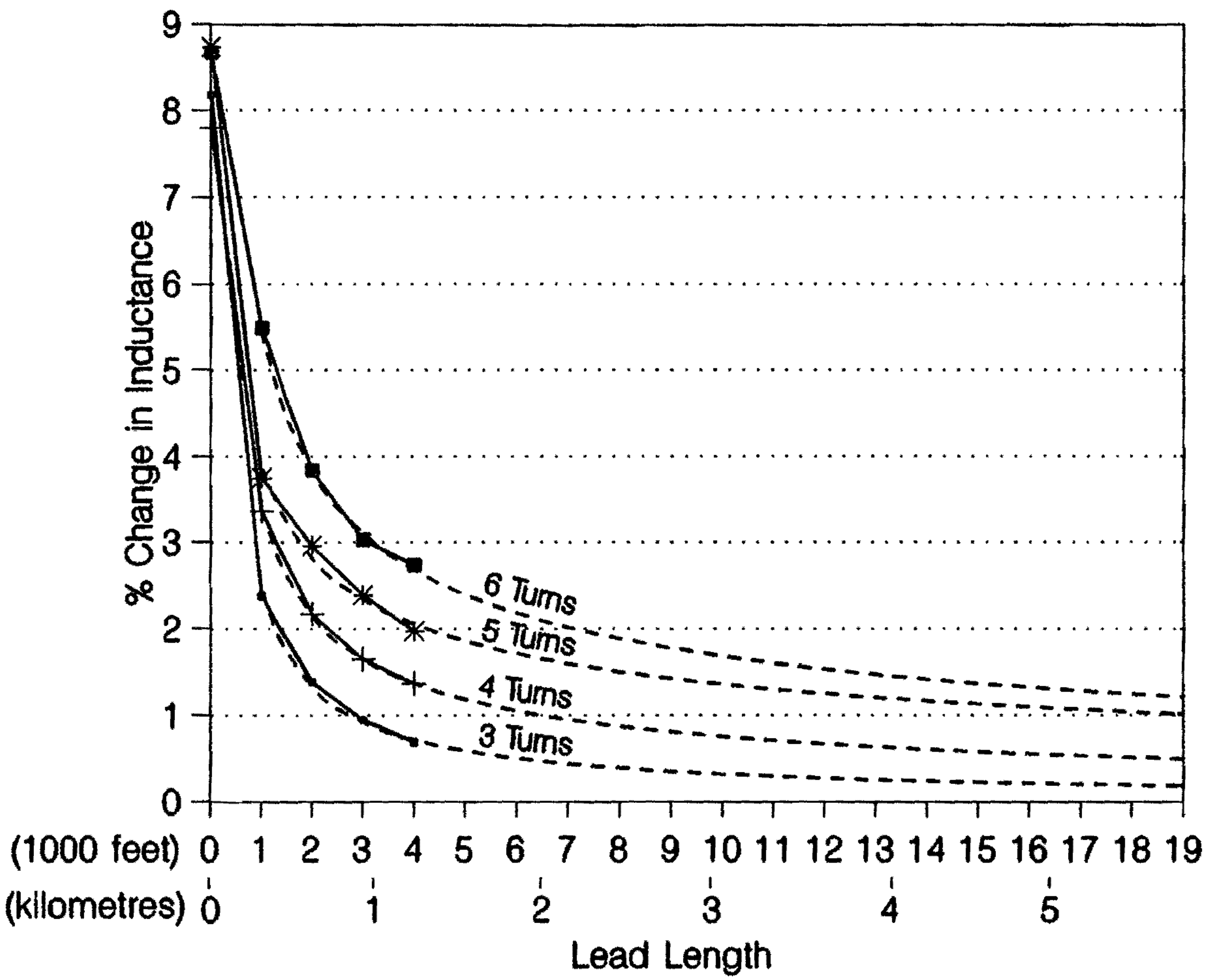

Figure 3. Effect of Lead Length on Percent Change in Inductance for a Large Car

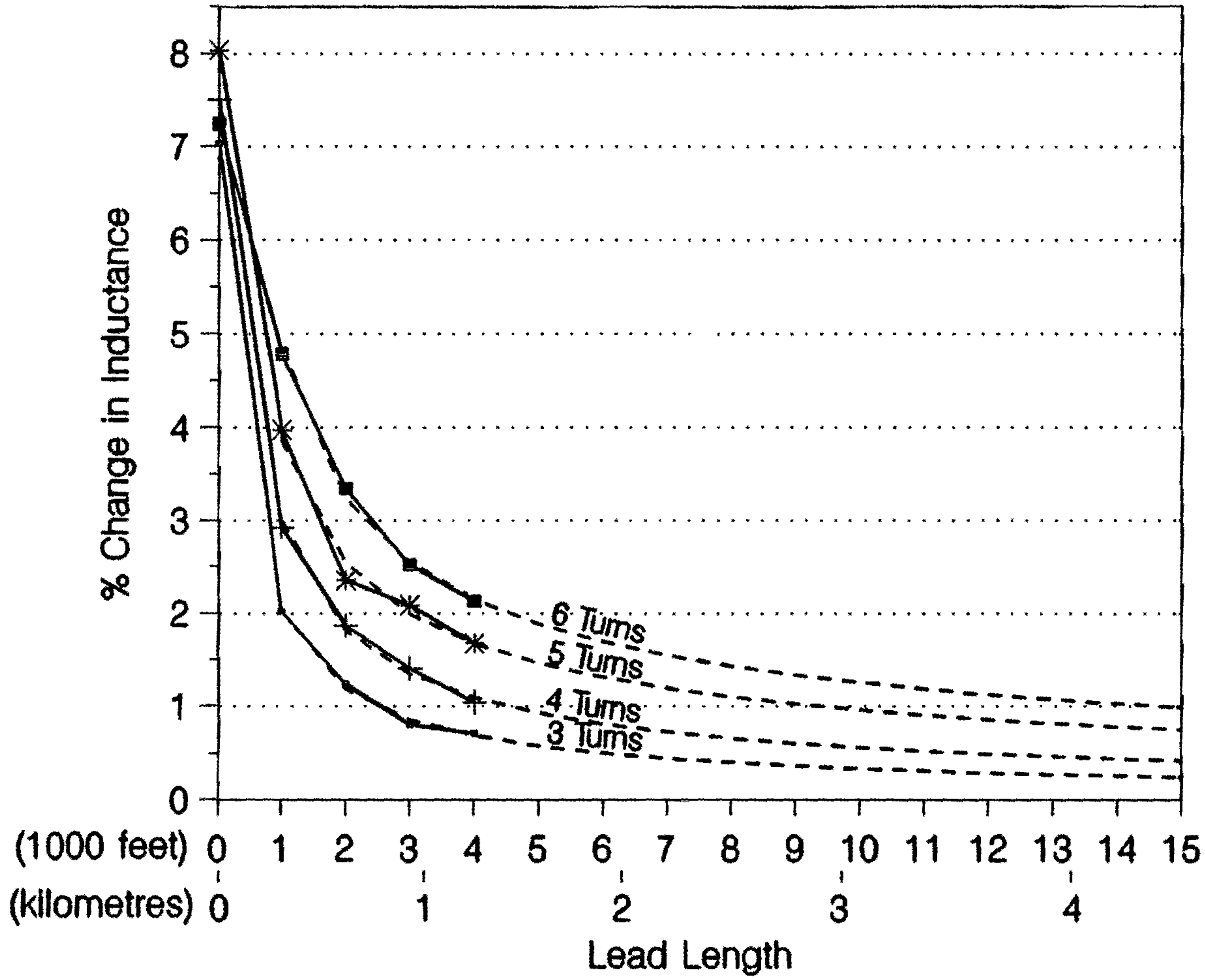

Figure 4. Effect of Lead Length on Percent Change in Inductance for a Small Car

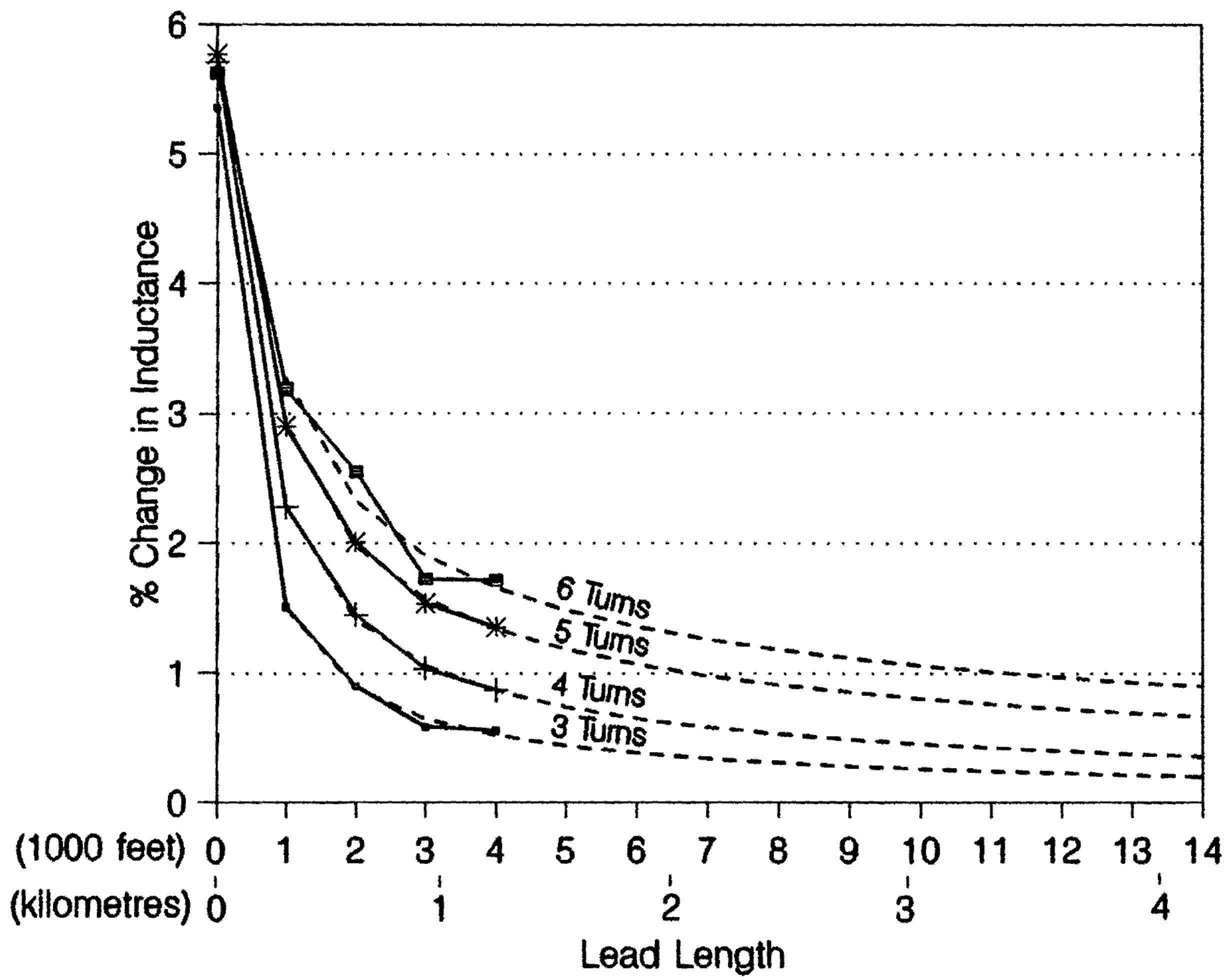

Figure 5. Effect of Lead Length on Percent Change in Inductance for a Pickup Truck

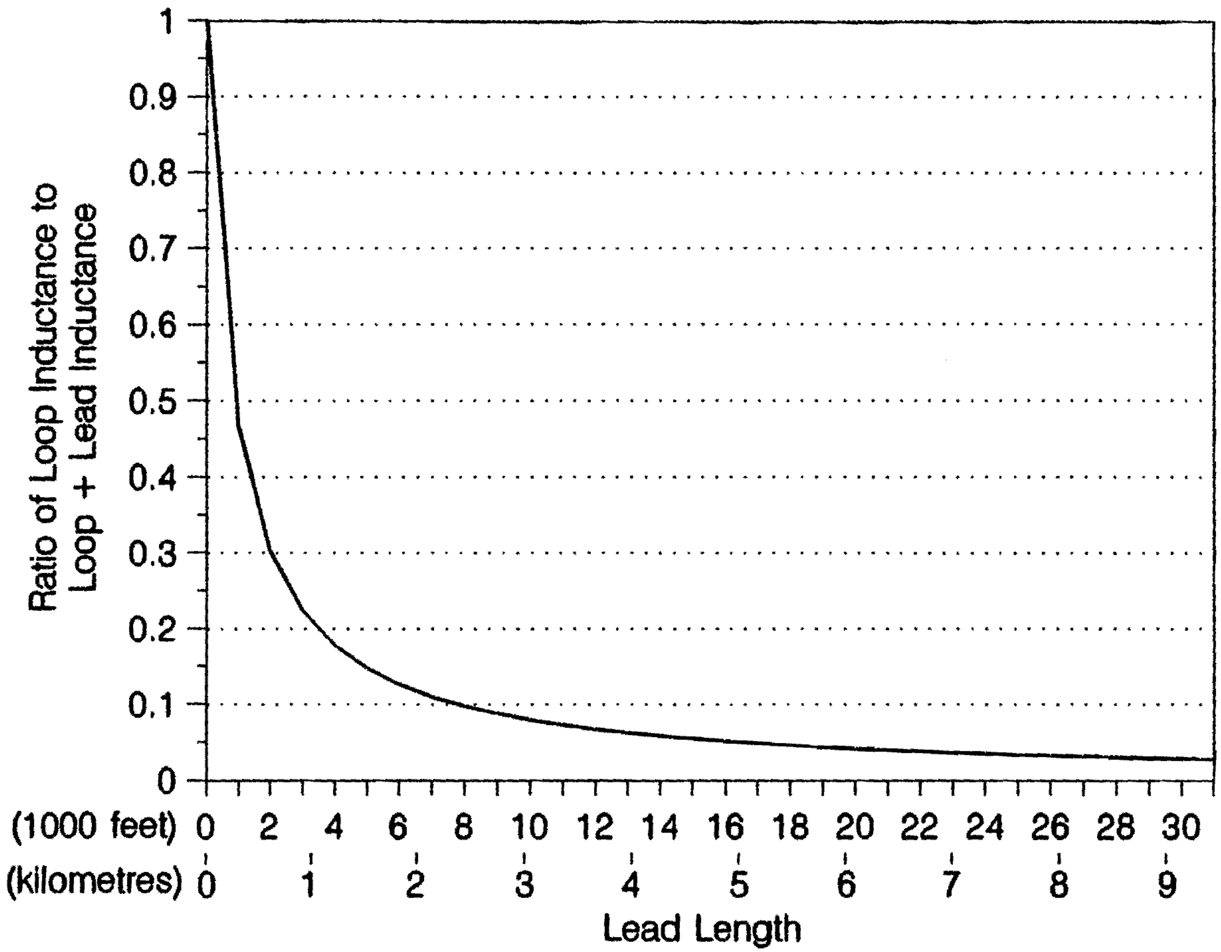

Figure 6. Effect of Loop Inductance to System Inductance with Long Lead Lengths

4.2 DETECTION OF ODD SIZED VEHICLES

The detection of odd sized vehicles, namely motorcycles and high profile trucks, is difficult under normal circumstances. With a long lead length, accurate detection becomes even more difficult. At 1,220 meters (4,000 feet), detection of both vehicles was possible on medium and high sensitivity levels and with four, five or six turns of wire. On high sensitivity, researchers observed 100 percent accurate detections on all detector units with 3, 4, 5 or 6 turns of wire. However, on medium sensitivity, the accuracy of detections depended on the detector unit used during testing. Each detector unit has a different threshold value of percent change in inductance required for vehicle detection. One detector unit detected with an accuracy of 100% on medium sensitivity, while another detected a very small percentage of vehicles. Therefore, when choosing a maximum lead length for design purposes, the detector unit limitations must be taken into consideration.

In order to help clarify the odd-sized vehicles' detection capabilities, the frequency change caused by the presence of each vehicle was again measured for the various lead lengths. The frequency values were converted to an inductance and then the percent change in inductance caused by the vehicle was calculated. The values were analyzed as a log-log distribution in the same manner as described earlier for the passenger vehicles. Table 3 identifies the R^2 values for each regression model. Figures 7 and 8 show the resulting best fit lines for extrapolation purposes for the motorcycle, driven through the center of the loop, and the high profile truck, respectively.

Table 3. Coefficients of Determination for the Linear Regression Models for the Motorcycle and High Profile Truck

Number of Wire Turns	Motorcycle	High Profile Truck
3	0.9299	0.9602
4	0.9943	0.9507
5	0.9757	0.9807
6	0.9900	0.9176

Figure 7 identifies that for accurate detections of a motorcycle on low sensitivity, the maximum possible lead length is around 457 meters (1,500 feet) for six turns of wire as shown in Table 4. For four and five turns of wire, the maximum lead length is about 305 meters (1,000 feet) and for three turns of wire, the maximum lead length is about 152 meters (500 feet). The maximum lead lengths for medium and high sensitivity are mostly unknown, since accurate detections occurred at all measured lead lengths. However, extrapolation of the data in Figure 7 indicates that lead lengths may be as long as 3,354 meters (11,000 feet) for medium sensitivity and may be as long as 9,146 or 12,195 meters (29,987 or 39,984 feet) for high sensitivity. Again, due to the variable nature of extrapolation procedures, these are only estimated values.

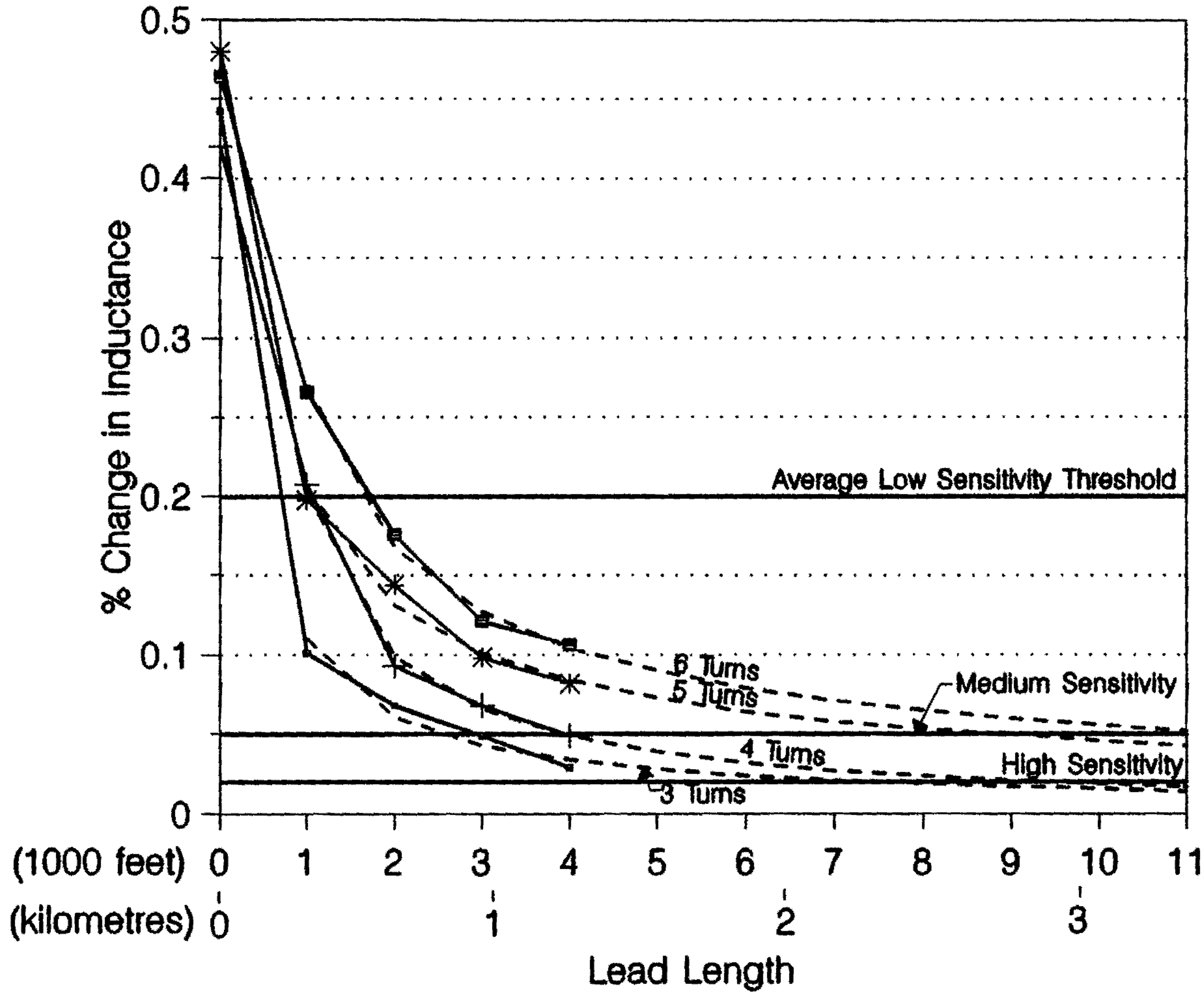

Figure 7. Effect of Lead Length on Percent Change in Inductance for a Motorcycle

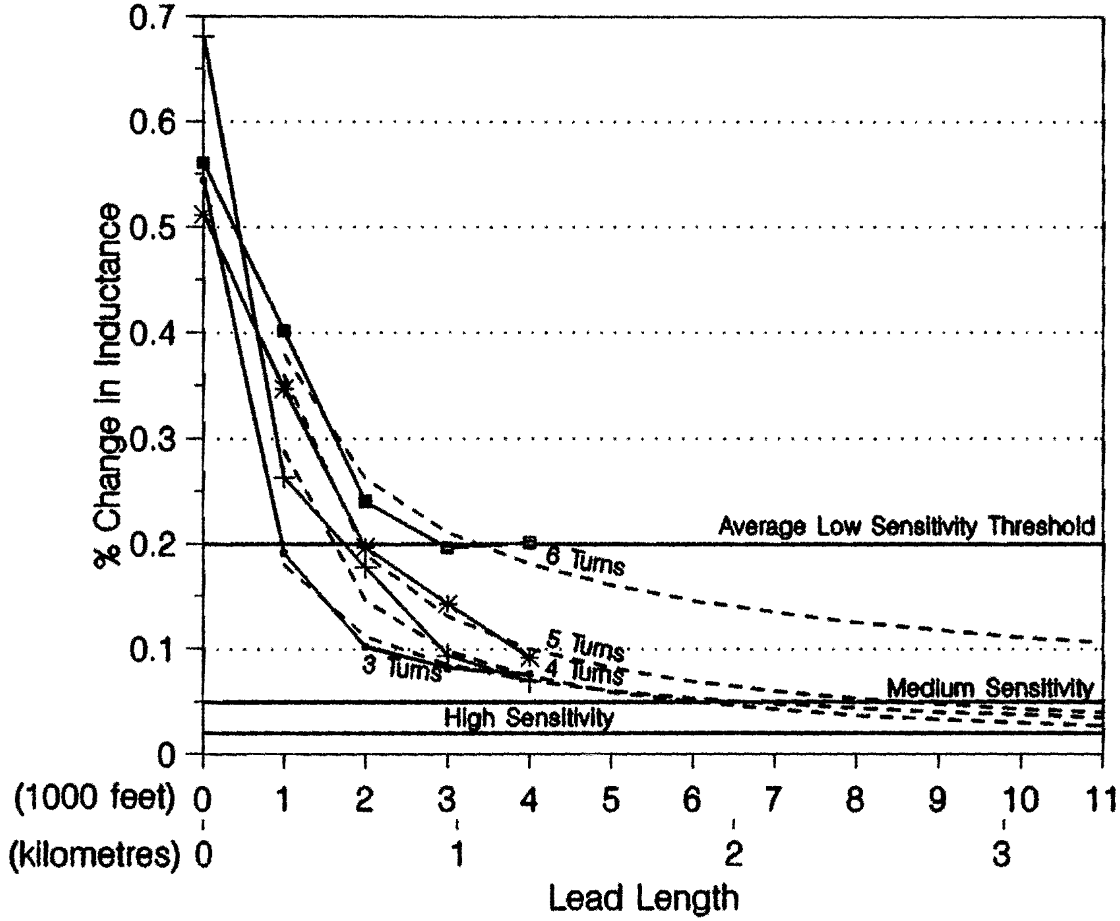

Figure 8. Effect of Lead Length on Percent Change in Inductance for the Midpoint of the Trailer of a High Profile Truck

Table 4. Maximum Lead Lengths in Meters (Feet) Possible for Accurate Detections of a Motorcycle

Sensitivity Level	3 Wire Turns	4 Wire Turns	5 Wire Turns	6 Wire Turns
Low	152 (500)	305 (1,000)	320 (1,050)	457 (1,500)
Medium	762 (2,500)	1,189 (3,900)	>1,220 (> 4,000)	1,220 (> 4,000)
High	>1,220 (> 4,000)	>1,220 (> 4,000)	>1,220 (> 4,000)	> 1,220 (> 4,000)

Figure 8 identifies the maximum lead lengths possible for detection of the mid-point of the trailer of a high profile truck. This point was chosen as the critical point because for a detector unit to hold the call in the presence mode, the detector unit must detect all parts of the truck, including the center of the trailer. The center of the trailer is the portion of the truck that is farthest from the pavement, and thus creates the smallest change in inductance in the loop system. The ability of a detector unit to detect a high profile truck and hold the call while the truck is on the loop is dependent upon the mid-point of the trailer.

Table 5 shows the measured maximum lead lengths for detecting the midpoint of the trailer of the high profile truck. The major constraining criteria for detecting high profile trucks occurs on low sensitivity. No accurate detections were recorded on low sensitivity and 1,220 meters (4,000 feet) of lead wire, even with 6 wire turns. On medium and high sensitivity, however, all three models of detector units had no problem detecting the high profile truck at a lead length of 1,220 meters (4,000 feet).

By extrapolating the data in Figure 8, researchers estimated the maximum lead lengths possible for detecting a high profile truck on medium or high sensitivity in the presence mode of operation. The extrapolation of the data indicate that high profile trucks may be detected on medium sensitivity with lead lengths around 1,830 to 2,439 meters (6,000 to 8,000 feet). High profile trucks may also be accurately detected on high sensitivity with lead lengths between 7,622 and 76,220 meters (25,000 and 250,000 feet). Due to the variability inherent in the extrapolation procedure, these lead length estimates are considered highly variable and questionable.

Table 5. Maximum Lead Lengths in Meters (Feet) Possible for Accurate Detection of the Midpoint of the Trailer of a High Profile Truck

Sensitivity Level	3 Wire Turns	4 Wire Turns	5 Wire Turns	6 Wire Turns
Low	259 (850)	442 (1,450)	572 (1,875)	1,006 (3,300)
Medium	> 1,220 (> 4,000)	>1,220 (>4,000)	> 1,220 (> 4,000)	> 1,220 (> 4,000)
High	> 1,220 (>4,000)	> 1,220 (> 4,000)	> 1,220 (>4,000)	> 1,220 (> 4,000)

4.3 SUMMARY

In the detection of vehicles with unusually long lead lengths, the constraining vehicles are the motorcycle and the high profile truck. The motorcycle requires the shortest lead lengths, but motorcycles are not always a major part of the vehicle stream. If motorcycles are not part of the vehicle stream, high profile trucks are the next most restricting vehicle. High profile trucks allow slightly larger lead lengths than motorcycles, but the lead lengths are still substantially less than lead lengths that can be used with standard passenger cars.

Testing of lead lengths stopped at 1,220 meters (4,000 feet). The data collected from this portion of the study identified that all five types of design vehicles will be accurately detected with a 1,220 meter 4,000 foot lead if medium or high sensitivity and 5 or 6 turns of wire are used. Any combination of smaller wire turns with low or medium sensitivity will fail to accurately detect the motorcycle and high profile truck. The analysis of the data also indicate that accurate detections are possible with much greater lead lengths. High profile trucks make up a substantial portion of freeway traffic in most parts of the country, so their detection is important for a freeway management system.

5.0 CONCLUSIONS AND RECOMMENDATIONS

The results of these tests provide important information regarding the successful use and implementation of induction loop detectors on freeways. While the results are not entirely conclusive, several trends did develop during the analysis of the data. The recommendations which follow are the result of these trends and provide the transportation engineer with some insight into the effective use of induction loop detectors in a freeway management system.

5.1 RECOMMENDED LIMITS OF LEAD LENGTH

Researchers successfully tested lead lengths up to 1,220 meters (4,000 feet) in the controlled testing environment. The two passenger cars and the pickup truck were always detected at 1,220 meters (4,000 feet) on all sensitivity levels with 3, 4, 5, and 6 turns of wire. The analysis of data indicate that much longer lead lengths can be utilized for detecting passenger cars, with the smallest lead length being 4,270 meters (14,000 feet) used with 3 turns of wire and a low sensitivity level. It should be noted that lead lengths of this size were not tested in the field during this study, but the data consistently identified that lead lengths of this size are possible. By utilizing higher sensitivity levels and a greater number of wire turns, lead lengths much larger than the scope of many freeway projects are possible.

Therefore, judging by the long lead lengths possible with passenger cars, the critical vehicles to consider in selecting an appropriate lead length are motorcycles and high profile trucks. The high profile truck detected well at all lead lengths, but the detection signal was not held throughout the length of the truck in many cases, especially on low sensitivity. In these instances, the detector units detected two vehicles instead of one high profile truck. When on medium sensitivity, maximum lead lengths for detecting the entire truck in the presence mode of operation are greater than 1,830 meters (6,000 feet), depending on the number of wire turns. On low sensitivity, maximum lead lengths are between 244 and 915 meters (800 and 3,000 feet). Therefore, if a large percentage of the freeway traffic is composed of high profile trucks, a medium sensitivity level should be utilized in order to allow for greater flexibility in the design of the loop detector locations.

The motorcycle was the most difficult vehicle to detect, due primarily to the fact that square loops were used during testing. Motorcycles are difficult to detect with square loops in normal situations, regardless of the lead length. However, successful detections are possible with long lead lengths assuming a medium or high sensitivity level. On medium sensitivity, a lead length of between 762 and 3,350 meters (2,500 and 11,000 feet) of lead wire accurately detect motorcycles, depending on the number of wire turns. Generally speaking, motorcycles do not comprise a large percentage of urban freeway traffic, and their detection for volume counting is not important to the freeway management process. On the other hand, detection of motorcycles may be important to speed measurement and analysis.

6.0 REFERENCES

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APPENDIX A

DIMENSIONS OF ODD SIZED VEHICLES

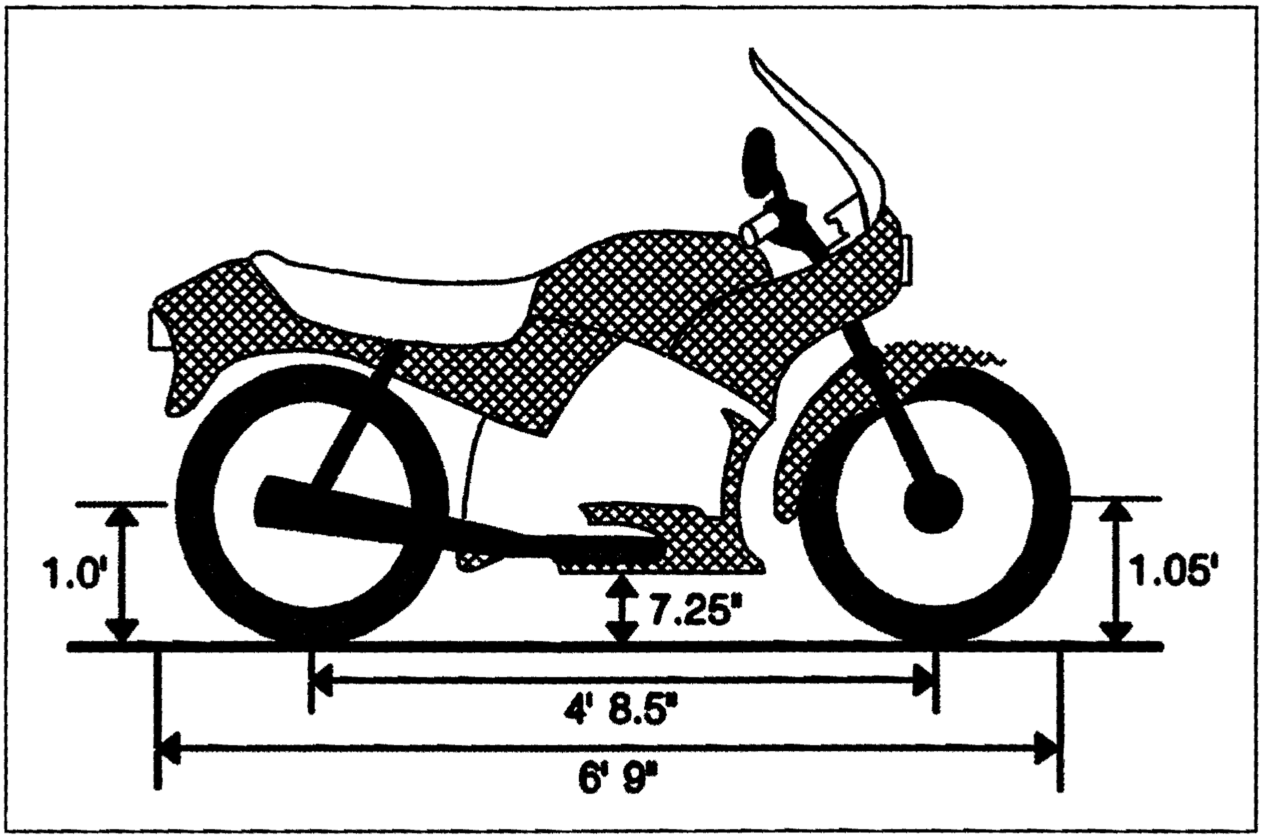

Figure A-1. Dimensions of the 1982 Suzuki 3006SL, Motorcycle
Note: 1 foot = .3048 meters and 1 inch = 2.54 centimeters

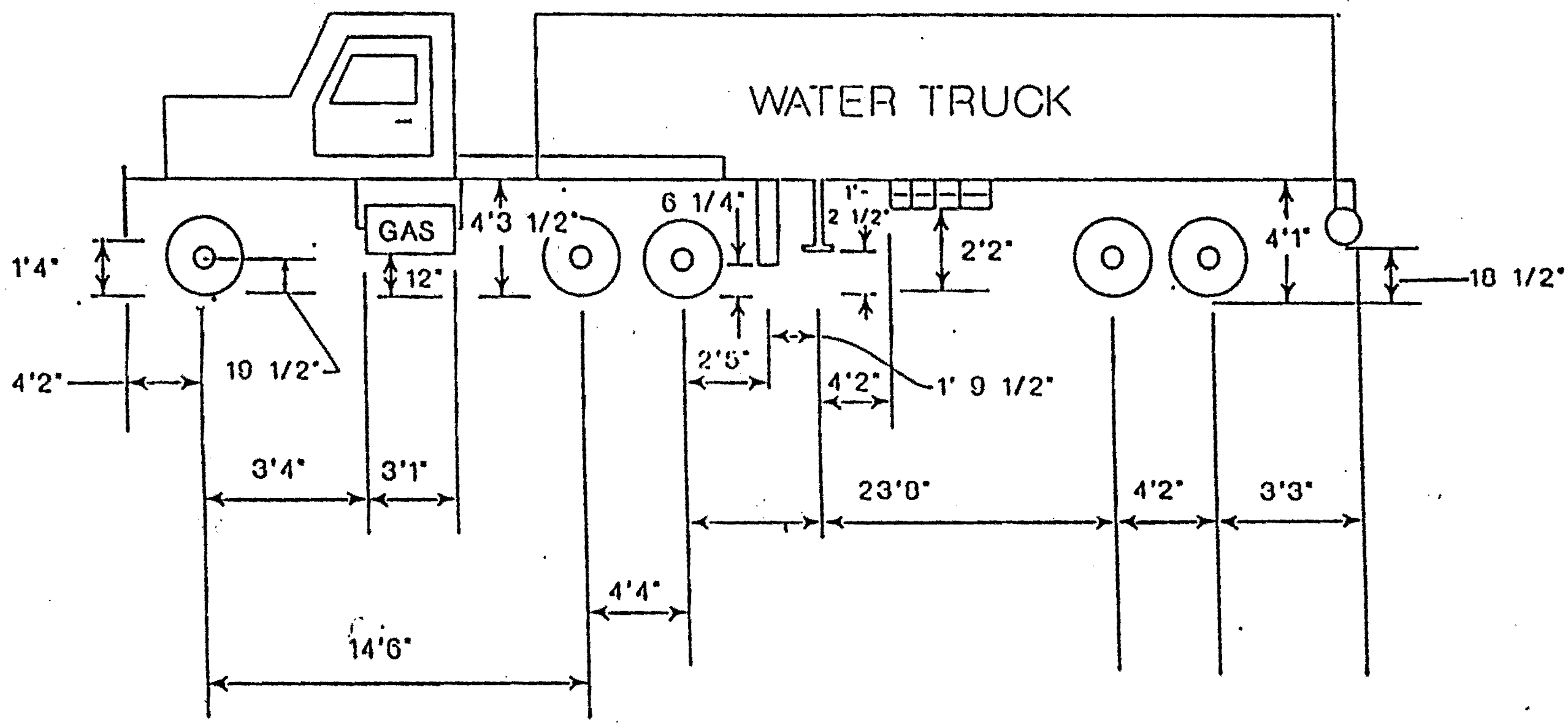

Figure A-2. Dimensions of the Kenworth Tractor-Trailer Combination
Note: 1 foot = .3048 meters and 1 inch = 2.54 centimeters.

APPENDIX B

PERCENT DETECTIONS WITH VARIOUS LEAD LENGTHS

Table B-1. Percent Accurate Detections with a 1,220 m (4,000 ft.) Lead Length and 6 Turns of Wire

Vehicle	Speed	Detector Systems 103SS			Detector Systems 102SS			Sarasota 515TX		
		low	med	hi	low	med	hi	min	med	max
Large Car	20	100	100	100	100	100	100	100	100	100
	40	100	100	100	100	100	100	100	100	100
	60	100	100	100	100	100	100	100	100	100
	80	100	100	100	100	100	100	100	100	100
Small Car	20	100	-	-	100	-	-	100	-	-
	40	100	-	-	100	-	-	100	100	-
	60	100	-	-	100	-	-	100	100	-
	70	100	-	-	100	-	-	100	-	-
Pick-up Truck	20	100	100	100	100	100	100	100	100	100
	40	100	100	100	100	100	100	100	100	100
	60	100	100	100	100	100	100	100	100	100
	80	100	100	100	100	100	100	100	100	100
High Profile Truck	20	0	100	100	100	100	100	0	100	100
	40	0	100	100	100	100	100	0	100	100
	60	0	100	100	100	100	100	0	100	100
Motor-Cycle	20	0	20	100	57	100	100	0	100	100
	40	0	0	100	0	100	100	0	100	-
	60	0	0	86	20	100	100	0	100	-

Table B-2. Percent Accurate Detections with a 1,220 m (4,000 ft.) Lead Length and 5 Turns of Wire

Vehicle	Speed	Detector Systems 103SS			Detector Systems 102SS			Sarasota 515TX		
		low	med	hi	low	med	hi	min	med	max
Large Car	20	100	-	-	100	-	-	100	-	-
	40	100	-	-	100	-	-	100	-	-
	60	100	-	-	100	-	-	100	-	-
	80	100	-	-	100	-	-	100	-	-
Small Car	20	100	100	100	100	100	-	100	100	-
	40	100	-	-	100	-	-	100	100	-
	60	100	-	-	100	-	-	100	-	-
	70	100	-	-	100	-	-	100	-	-
Pick-up Truck	20	100	-	-	-	100	-	100	-	-
	40	100	-	-	-	100	-	100	-	-
	60	-	-	-	-	100	-	100	-	-
	80	-	-	-	-	-	-	-	-	-
High Profile Truck	20	0	100	-	80	100	-	0	100	-
	40	0	100	-	100	100	-	0	100	-
	60	0	100	-	100	-	-	0	100	-
Motor-Cycle	20	0	0	100	0	100	-	0	100	-
	40	-	-	100	-	100	-	0	100	-
	60	-	-	0	-	100	-	-	100	-

Table B-3. Percent Accurate Detections with a 1,220 m (4,000 ft.) Lead Length and 4 Turns of Wire

Vehicle	Speed	Detector Systems 103SS			Detector Systems 102SS			Sarasota 515TX		
		low	med	hi	low	med	hi	min	med	max
Large Car	20	-	-	-	-	-	-	-	-	-
	40	-	-	-	-	-	-	-	-	-
	60	-	-	-	-	-	-	-	-	-
	80	-	-	-	-	-	-	-	-	-
Small Car	20	-	-	-	-	-	-	-	-	-
	40	-	-	-	-	-	-	-	-	-
	60	-	-	-	-	-	-	-	-	-
	70	-	-	-	-	-	-	-	-	-
Pick-up Truck	20	-	-	-	-	-	-	-	-	-
	40	-	-	-	-	-	-	-	-	-
	60	-	-	-	-	-	-	-	-	-
	80	-	-	-	-	-	-	-	-	-
High Profile Truck	20	0	25	100	0	100	-	0	100	-
	40	-	-	100	-	100	-	-	100	-
	60	-	-	-	-	-	-	-	-	-
Motor-Cycle	20	0	0	100	0	100	-	-	-	-
	40	-	-	100	-	100	-	-	100	-
	60	-	-	-	-	-	-	-	-	-

Table B-4. Percent Accurate Detections with a 1,220 m (4,000 ft.) Lead Length and 3 Turns of Wire

Vehicle	Speed	Detector Systems 103SS			Detector Systems 102SS			Sarasota 515TX		
		low	med	hi	low	med	hi	min	med	max
Large Car	20	100	-	-	100	-	-	100	-	-
	40	100	-	-	100	-	-	100	-	-
	60	100	-	-	100	-	-	100	-	-
	80	80	-	-	100	-	-	100	-	-
Small Car	20	100	-	-	100	-	-	100	-	-
	40	100	-	-	100	-	-	100	-	-
	60	100	-	-	100	-	-	100	-	-
	70	-	-	-	-	-	-	-	-	-
Pick-up Truck	20	100	-	-	100	-	-	100	-	-
	40	100	-	-	100	-	-	100	-	-
	60	100	-	-	100	-	-	100	-	-
	80	25	100	-	100	-	-	100	-	-
High Profile Truck	20	0	0	100	0	100	-	0	0	100
	40	-	0	100	-	100	-	-	-	100
	60	-	-	-	-	-	-	-	-	-
Motor-Cycle	20	-	0	100	0	100	-	-	0	100
	40	-	0	0	-	100	-	-	-	100
	60	-	0	0	-	50	100	-	-	100

Table B-5. Percent Accurate Detections with a 915 m (3000 ft.) Lead Length and 3 Turns of Wire

Vehicle	Speed	Detector Systems 103SS			Detector Systems 102SS			Sarasota 515TX		
		low	med	hi	low	med	hi	min	med	max
High Profile Truck	20	0	0	100	0	100	-	0	100	100
	40	-	-	100	-	100	-	-	0	0
	60	-	-	-	-	-	-	-	-	-
Motor-Cycle	20	0	0	100	0	100	-	0	0	100
	40	-	-	33	-	100	-	-	-	100
	60	-	-	-	-	-	-	-	-	-

Table B-6. Percent Accurate Detections with a 610 m (2000 ft.) Lead Length and 4 Turns of Wire

Vehicle	Speed	Detector Systems 103SS			Detector Systems 102SS			Sarasota 515TX		
		low	med	hi	low	med	hi	min	med	max
High Profile Truck	20	0	100	-	100	100	-	0	100	-
	40	0	100	-	100	-	-	0	100	-
	60	-	-	-	-	-	-	-	-	-

Table B-7. Percent Accurate Detections with a 610 m (2000 ft.) Lead Length and 3 Turns of Wire

Vehicle	Speed	Detector Systems 103SS			Detector Systems 102SS			Sarasota 515TX		
		low	med	hi	low	med	hi	min	med	max
High Profile Truck	20	0	100	100	0	100	100	0	100	100
	40	0	100	100	0	100	100	0	100	100
	60	-	-	-	-	-	-	-	-	-

APPENDIX C

LOG-LOG EXTRAPOLATION ANALYSIS AND REGRESSION COEFFICIENTS FOR THE LEAD LENGTH STUDY

Table C-1. Regression Data for the Percent Change in Inductance of a Large Car

Lead Length (x,feet)	3 Wire Turns Best Fit Line (ln y)	3 Wire Turns Best Fit Line (y)	4 Wire Turns Best Fit Line (ln y)	4 Wire Turns Best Fit Line (y)	5 Wire Turns Best Fit Line (ln y)	5 Wire Turns Best Fit Line (y)	6 Wire Turns Best Fit Line (ln y)	6 Wire Turns Best Fit Line (y)
0	1.746	5.734	1.812	6.122	1.910	6.753	2.044	7.724
1000	1.160	3.189	1.391	4.020	1.567	4.794	1.755	5.781
2000	0.573	1.774	0.971	2.640	1.225	3.403	1.465	4.326
3000	-0.013	0.987	0.550	1.733	0.882	2.415	1.175	3.238
4000	-0.600	0.549	0.129	1.138	0.539	1.715	0.885	2.423
5000	-1.187	0.305	-0.291	0.747	0.196	1.217	0.595	1.813
6000	-1.773	0.170	-0.712	0.491	-0.146	0.864	0.305	1.357
7000	-2.360	0.094	-1.132	0.322	-0.489	0.613	0.016	1.016
8000	-2.947	0.053	-1.553	0.212	-0.832	0.435	-0.274	0.760
9000	-3.533	0.029	-1.974	0.139	-1.174	0.309	-0.564	0.569
10000	-4.120	0.016	-2.394	0.091	-1.517	0.219	-0.854	0.426
11000	-4.706	0.009	-2.815	0.060	-1.860	0.156	-1.144	0.319

3 Wire Turns (ln y):
Estimated Constant = 1.74644
Regression Coeff. = -0.00059

4 Wire Turns (ln y):
Estimated Constant = 1.81193
Regression Coeff. = -0.00042

5 Wire Turns (ln y):
Estimated Constant = 1.91004
Regression Coeff. = -0.00034

6 Wire Turns (ln y):
Estimated Constant = 2.04439
Regression Coeff. = -0.00029

Table C-2. Regression Data for the Percent Change in Inductance of a Small Car

Lead Length (x,feet)	3 Wire Turns Best Fit Line (ln y)	3 Wire Turns Best Fit Line (y)	4 Wire Turns Best Fit Line (ln y)	4 Wire Turns Best Fit Line (y)	5 Wire Turns Best Fit Line (ln y)	5 Wire Turns Best Fit Line (y)	6 Wire Turns Best Fit Line (ln y)	6 Wire Turns Best Fit Line (y)
0	1.563	4.771	1.756	5.789	1.871	6.494	1.905	6.721
1000	1.012	2.751	1.288	3.625	1.493	4.449	1.596	4.933
2000	0.462	1.587	0.820	2.270	1.114	3.048	1.287	3.621
3000	-0.089	0.915	0.352	1.421	0.736	2.088	0.978	2.658
4000	-0.639	0.528	-0.116	0.890	0.358	1.431	0.668	1.951
5000	-1.189	0.304	-0.585	0.557	-0.020	0.980	0.359	1.432
6000	-1.740	0.176	-1.053	0.349	-0.398	0.671	0.050	1.051
7000	-2.290	0.101	-1.521	0.219	-0.777	0.460	-0.259	0.771
8000	-2.840	0.058	-1.989	0.137	-1.155	0.315	-0.569	0.566
9000	-3.391	0.034	-2.457	0.086	-1.533	0.216	-0.878	0.416
10000	-3.941	0.019	-2.925	0.054	-1.911	0.148	-1.187	0.305
11000	-4.492	0.011	-3.393	0.034	-2.290	0.101	-1.496	0.224

3 Wire Turns (ln y):
Estimated Constant = 1.56251
Regression Coeff. = -0.00055

4 Wire Turns (ln y):
Estimated Constant = 1.75597
Regression Coeff. = -0.00047

5 Wire Turns (ln y):
Estimated Constant = 1.87094
Regression Coeff. = -0.00038

6 Wire Turns (ln y):
Estimated Constant = 1.90521
Regression Coeff. = -0.00031

Table C-3. Regression Data for the Percent Change in Inductance of a Pickup Truck

Lead Length (x,feet)	3 Wire Turns Best Fit Line (ln y)	3 Wire Turns Best Fit Line (y)	4 Wire Turns Best Fit Line (ln y)	4 Wire Turns Best Fit Line (y)	5 Wire Turns Best Fit Line (ln y)	5 Wire Turns Best Fit Line (y)	6 Wire Turns Best Fit Line (ln y)	6 Wire Turns Best Fit Line (y)
0	1.268	3.555	1.478	4.386	1.558	4.749	1.580	4.856
1000	0.722	2.059	1.023	2.781	1.204	3.334	1.281	3.601
2000	0.176	1.192	0.567	1.763	0.850	2.341	0.982	2.670
3000	-0.371	0.690	0.112	1.118	0.497	1.643	0.683	1.980
4000	-0.917	0.400	-0.344	0.709	0.143	1.154	0.384	1.468
5000	-1.463	0.231	-0.800	0.449	-0.211	0.810	0.085	1.088
6000	-2.010	0.134	-1.255	0.285	-0.564	0.569	-0.214	0.807
7000	-2.556	0.078	-1.711	0.181	-0.918	0.399	-0.514	0.598
8000	-3.103	0.045	-2.167	0.115	-1.272	0.280	-0.813	0.444
9000	-3.649	0.026	-2.622	0.073	-1.626	0.197	-1.112	0.329
10000	-4.195	0.015	-3.078	0.046	-1.979	0.138	-1.411	0.244
11000	-4.742	0.009	-3.534	0.029	-2.333	0.097	-1.710	0.181

3 Wire Turns (ln y):
Estimated Constant = 1.26849
Regression Coeff. = -0.00055

4 Wire Turns (ln y):
Estimated Constant = 1.47846
Regression Coeff. = -0.00046

5 Wire Turns (ln y):
Estimated Constant = 1.55787
Regression Coeff. = -0.00035

6 Wire Turns (ln y):
Estimated Constant = 1.58022
Regression Coeff. = -0.00030

Table C-4. Regression Data for the Percent Change in Inductance of a Motorcycle

Lead Length (x,feet)	3 Wire Turns		4 Wire Turns		5 Wire Turns		6 Wire Turns	
	Best Fit Line (ln y)	Best Fit Line (y)	Best Fit Line (ln y)	Best Fit Line (y)	Best Fit Line (ln y)	Best Fit Line (y)	Best Fit Line (ln y)	Best Fit Line (y)
0	-1.236	0.290	-1.020	0.360	-0.976	0.377	-0.889	0.411
1000	-1.854	0.157	-1.562	0.210	-1.399	0.247	-1.263	0.283
2000	-2.471	0.085	-2.103	0.122	-1.823	0.162	-1.637	0.195
3000	-3.088	0.046	-2.645	0.071	-2.247	0.106	-2.011	0.134
4000	-3.705	0.025	-3.186	0.041	-2.671	0.069	-2.385	0.092
5000	-4.322	0.013	-3.728	0.024	-3.094	0.045	-2.759	0.063
6000	-4.939	0.007	-4.269	0.014	-3.518	0.030	-3.133	0.044
7000	-5.556	0.004	-4.811	0.008	-3.942	0.019	-3.507	0.030
8000	-6.174	0.002	-5.352	0.005	-4.366	0.013	-3.881	0.021
9000	-6.791	0.001	-5.894	0.003	-4.789	0.008	-4.256	0.014
10000	-7.408	0.001	-6.435	0.002	-5.213	0.005	-4.630	0.010
11000	-8.025	0.000	-6.977	0.001	-5.637	0.004	-5.004	0.007

3 Wire Turns (ln y):
Estimated Constant = -1.23648
Regression Coeff. = -0.00062

4 Wire Turns (ln y):
Estimated Constant = -1.02043
Regression Coeff. = -0.00054

5 Wire Turns (ln y):
Estimated Constant = -0.97556
Regression Coeff. = -0.00042

6 Wire Turns (ln y):
Estimated Constant = -0.88902
Regression Coeff. = -0.00037

Table C-5. Regression Data for the Percent Change in Inductance of a High Profile Truck (Mid-Trailer)

Lead Length (x,feet)	3 Wire Turns Best Fit Line (ln y)	3 Wire Turns Best Fit Line (y)	4 Wire Turns Best Fit Line (ln y)	4 Wire Turns Best Fit Line (y)	5 Wire Turns Best Fit Line (ln y)	5 Wire Turns Best Fit Line (y)	6 Wire Turns Best Fit Line (ln y)	6 Wire Turns Best Fit Line (y)
0	-0.969	0.380	-0.575	0.563	-0.673	0.510	-0.676	0.509
1000	-1.447	0.235	-1.136	0.321	-1.105	0.331	-0.953	0.386
2000	-1.925	0.146	-1.697	0.183	-1.537	0.215	-1.230	0.292
3000	-2.403	0.090	-2.258	0.105	-1.969	0.140	-1.507	0.221
4000	-2.881	0.056	-2.818	0.060	-2.401	0.091	-1.785	0.168
5000	-3.360	0.035	-3.379	0.034	-2.833	0.059	-2.062	0.127
6000	-3.838	0.022	-3.940	0.019	-3.264	0.038	-2.339	0.096
7000	-4.316	0.013	-4.501	0.011	-3.696	0.025	-2.616	0.073
8000	-4.794	0.008	-5.061	0.006	-4.128	0.016	-2.893	0.055
9000	-5.272	0.005	-5.622	0.004	-4.560	0.010	-3.170	0.042
10000	-5.751	0.003	-6.183	0.002	-4.992	0.007	-3.448	0.032
11000	-6.229	0.002	-6.744	0.001	-5.424	0.004	-3.725	0.024

3 Wire Turns (ln y):
Estimated Constant = -0.96863
Regression Coeff. = -0.00048

4 Wire Turns (ln y):
Estimated Constant = -0.57522
Regression Coeff. = -0.00056

5 Wire Turns (ln y):
Estimated Constant = -0.67275
Regression Coeff. = -0.00043

6 Wire Turns (ln y):
Estimated Constant = -0.67588
Regression Coeff. = -0.00028