ANALYSIS OF INDUCTANCE LOOP DETECTOR SENSITIVITIES

by

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for

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ABSTRACT

This report presents the results of a group of tests on the accuracy and sensitivity of inductance loops. The detection ability of deep buried loops to bicycles, motorcycles, MOPEDs, and high profile trucks are discussed. Also included is the effect of water and the effect of a manhole on the detector's sensitivity.

Deep buried loops were found to be unsuitable for detecting bicycles and MOPEDs. However, deep buried loops up to a depth of 15" did successfully detect and hold the call for high profile trucks.

Water did create a slight change in the loop inductance, but the TX series detector was able to adjust around the change. No effect on vehicle detection was found when the loop was flooded with water.

A manhole within the loop area did not detract from the loop's ability to accurately detect vehicles. The loop performed essentially the same as a loop located in an area without a manhole.

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INTRODUCTION

Purpose

Inductance loops play a major role in vehicle detection systems that provide data for use in traffic-actuated signal control and other surveillance systems. Induction loops detect the presence or passage of automobiles and trucks. Considering the wide variety of vehicles on the road today, it has become increasingly important to find a loop configuration that will accurately detect odd-sized vehicles. Odd-sized vehicles include motorcycles, mopeds, bicycles, and especially high profile trucks. This loop type should also be easy to install and relatively maintenance free.

Most loops in use today are rectangular surface loops and are not efficient enough to detect these vehicles. A recent study found that deep buried loops are as accurate in detecting automobiles as surface loops.(1) However, since damage by pavement movement, traffic flow, and construction equipment does not exist, deep buried loops require less maintenance. It is therefore desirable to determine if deep buried loops are sensitive enough to detect bicycles, MOPEDs, motorcycles and high profile trucks.

Several common practices used today during loop installation use up valuable time and may not even be necessary. One practice requires sealing the loop for protection from water and another is to avoid placing the loop near a manhole. Many professionals believe that water around a loop wire or the presence of a manhole near a loop has an adverse effect on a loop's accuracy. Therefore, it is desirable to determine what effect, if any, these conditions have on accurate inductance loop operation.

Objectives

The objective of this research effort is to establish a better understanding of induction loop detector sensitivity. The specific objectives of this research are:

1. To determine how sensitive deep buried skewed loop detectors are to bicycles, MOPEDs, and motorcycles for two, three, four and five turns of wire.
2. To determine how sensitive deep buried loop detectors are to high profile trucks for two, three, four and five turns of wire.
3. To determine how the presence of water around the loop wire in the conduit affects the detection ability of the loop for two, three, four, and five turns of wire.
4. To determine how the presence of a manhole in the loop area influences the sensitivity of a surface loop.

BACKGROUND

Principles of Detection

An inductance loop is composed of a detector unit, a lead-in cable, and an insulated wire (the loop) wound one or more times (each wind is known as a turn) in the pavement surface. The detector unit energizes the loop system RF circuit at a certain frequency. The loop becomes an inductive element, and, as a vehicle travels over the loop, the inductance of the loop decreases. The detector unit senses this change in peak frequency and interprets this as a vehicle presence if its magnitude exceeds the threshold value set on the detector.

Loop Inductance Measurements

A loop should contain more than 50 microhenries of inductance to operate effectively, and, depending on the size of the loop and the lead-in cable length, the loop requires a certain number of wire turns. The minimum number of turns needed for a certain loop size can be approximated as follows:

$$L=\frac{5PN^2}{N+10}$$

Where: L = Loop inductance in microhenries

P = Perimeter of the loop in feet

N = Number of turns of wire used

The actual inductance is determined in several ways. It is measured with an inductance meter or determined from the frequency by using the manufacturer's frequency verses inductance plot on the frequency meter. The inductance can also be calculated from the following relationship:

$$f=\frac{1}{2\Pi\sqrt{LC}}$$

Where: f = Frequency of the loop in hertz

L = Loop inductance in henries

C = Capacitance of the loop in picofarads

A loop's sensitivity can be adjusted. The detector unit has high, medium, and low settings which adjust a loop's sensitivity. The number of turns of wire also affects the sensitivity. A greater number of wire turns results in a greater detector sensitivity.

Loop Configurations in Bicycle Detection

Although many loop designs exist, the most common surface loop design used in the field is the 6' x 6' square. This design effectively detects automobiles and is easy to install. A recent study has shown, however, that this design does not accurately detect bicycle and motorcycle traffic. The study found that a 6' x 6' loop skewed 45 degrees to the direction of traffic is the best design for accurate detection of bicycles, MOPEDs, and motorcycles.(2) Other designs primarily used for bicycle and MOPED detection are shown in Figure 1.(3)

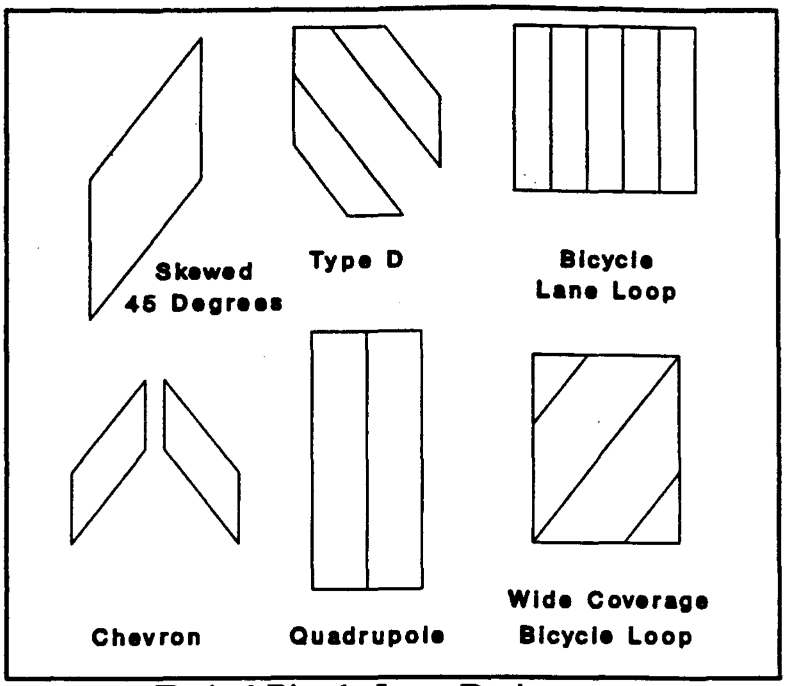


Figure 1: Typical Bicycle Loop Designs

Deep Buried Loops and Bicycle Detection

A loop installed below the pavement surface is known as a deep buried loop. A recent study showed that a 6' x 6' square twenty inch deep buried loop detects automobiles as well as a 6' x 6' square surface loop.(1) However, neither the surface loop nor the deep buried loop accurately detected bicycles, MOPEDs, or motorcycles possibly because of the square loop shape. For deep buried loops to be effective, small vehicle detection must be achieved at a sensitivity level that will not cause false detections from adjacent lanes. This is especially true if the loop is located in a bike lane.

Deep Buried Loops and High Profile Truck Detection

One type of vehicle which may be hard to detect with a deep buried loop is a high profile truck. High profile trucks sit at or about 51 inches off of the ground. With the loop buried at 20 inches below the surface, the truck bed is 71 inches (5.9 feet) away from the inductance loop. This distance may be too large for the loop inductance to change, so presence detection may not be possible.

For deep buried loops to be considered an acceptable loop alternative, high profile truck detection is necessary. If the detector only detects each axle, it falsely detects the passage of two vehicles. Large vehicles must be detected and allowed to pass through on the green phase. Non detection of these vehicles can cause jack-knifing, a longer start-up time delaying other traffic, and increased noise and air pollution resulting from high profile truck start-up.(3)

Effect of Water on a Loop

Common practice in surface loop installation is to seal the loop for protection from water and for holding the loop in place and away from traffic damage. Many believe that water affects the inductance of a loop, thereby degrading the loop's detection ability. However, a recent study in a laboratory proved that the presence of water around a loop produces only a small change in capacitance and frequency.(1) With the current state of modern detectors, this small change in frequency does not affect the ability of the detector to function accurately.

The Federal Highway Administration (FHWA) questioned the study because the study did not consider the effect the soil will have on the water saturated loop. The FHWA believes that water around a deep buried loop will change the inductance enough to trigger a false detection.(4) If water does not have any affect on a loop, sealing the loop 100% will not be necessary, thereby saving time and money.

Effect of a Manhole on a Loop

The FHWA recommends that traffic detectors should not operate within 10 feet of a manhole located in the roadway. This distance is required to allow for maintenance work on the manhole without disturbing the detector.(3) No studies, however, have been completed to determine the effect of metal objects, such as manholes, on detector sensitivity. This research effort examines the effect of a manhole on the sensitivity and detection ability of a surface loop.

STUDY DESIGN

Installation of Induction Loops

Two deep buried 6' x 6' square loops exist on University Drive near Avenue A. The loops are 15 inches and 20 inches below the pavement surface. Installation of a deep buried 6' x 6' loop skewed 45 degrees to the direction of traffic occurred in the 1200 block of Neal Pickett Drive in College Station, Texas.

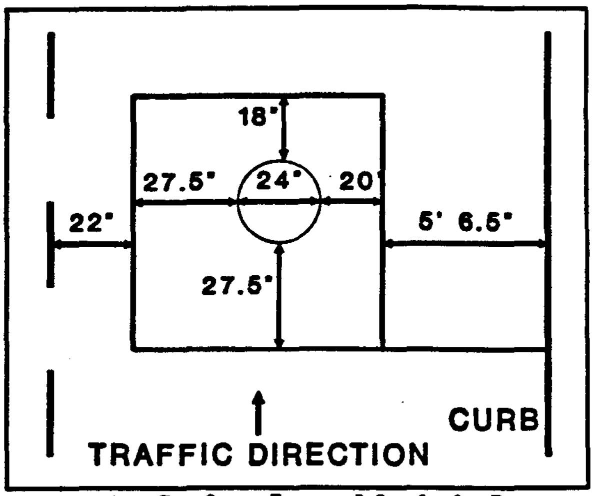


Figure 2: Surface Loop Manhole Layout

Due to the compaction of the subbase course prior to installation, the loop was placed only 10 inches below the surface.

Installation of a temporary 6' X 6' square surface loop occurred on Villa Maria Road between Texas Avenue and Wayside Drive in Bryan, Texas. The loop was placed around a 24 inch diameter manhole located in the far right hand eastbound lane as shown in Figure 2.

Small Vehicle Sensitivity Study

Manual observations using a Detector Systems Digital Loop Detector tested a MOPED, motorcycle, and two bicycles passing over the 45 degree deep buried skewed loop. The vehicles traveled on paths across the loop in both directions as shown in Figure 3.

Each vehicle made several passes on each path for each number of turn and sensitivity tested. Testing began with five wire turns and a high sensitivity level and slowly decreased. A medium frequency level remained throughout testing. A previous study has proven that no effect on vehicle detection exists for different frequency settings.(1) Due to time constraints, testing stopped when a vehicle made one pass on every path and no detections occurred. The number of turns and/or the sensitivity level then increased.

Observations also included the base frequency of the loop and the frequency as a vehicle passed over the loop. The frequency was used to determine the loop inductance and the percent change in inductance caused by a vehicle presence.

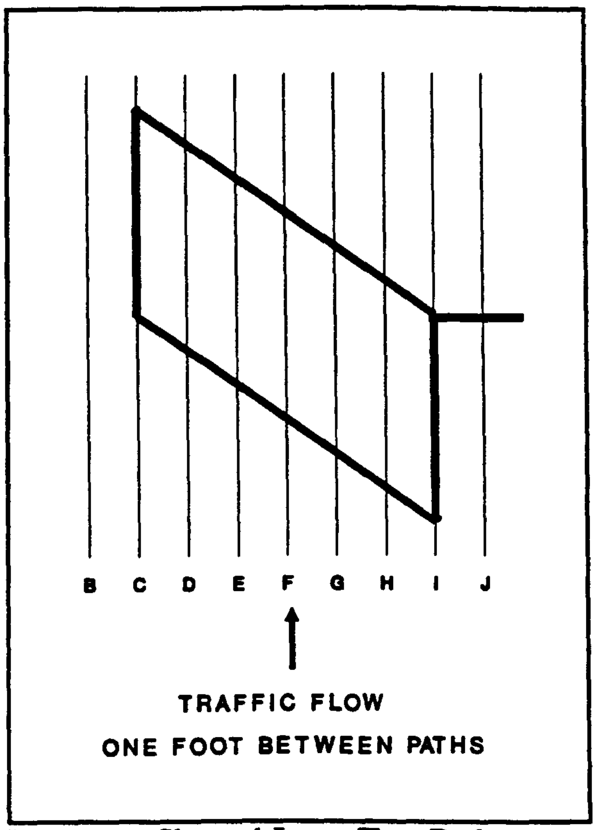


Figure 3: Skewed Loop Test Paths

High Profile Truck Sensitivity Study

Manual observations using the Detector Systems Digital Loop Detector observed the high profile truck passing over both the 15" deep and the 20" deep 6' X 6' square loops buried on University Drive. Observations included two, three, four and five turns of wire with low, medium, and high sensitivity settings. A medium frequency level remained throughout testing. The TTI water truck was used as the high profile truck. A sketch of this truck is included in Appendix E.

While the truck study was performed, the percent change in inductance of different sized vehicles was determined. The base frequency of the loop and the frequency as the vehicles passed over the loop were recorded.

Manhole Sensitivity Study

Using the Detector Systems Detector Unit, manual observations determined if the manhole affects a loop's accuracy. Observations began with two turns of wire and a low sensitivity setting. A medium frequency level remained throughout testing. Observations included 50 passes of random vehicles for each number of turn and sensitivity combination tested. The number of false detections from the adjacent lane (spillovers), and number of vehicles travelling in the adjacent lane were also recorded.

Water Sensitivity Study

Since an inductance meter could not be located, the inductance of the loop was directly calculated using the RF circuit frequency. Capacitance and frequency measurements were taken on the University Drive 20" deep buried loop for all turns of wire. About two gallons of regular tap water then filled the loop PVC conduit. Capacitance and frequency measurements were then remeasured for all turns of wire.

An incorrect hookup of the MICRONTA multimeter resulted in invalid capacitance measurements. Remeasurements revealed that the multimeter's scales were too high to register a capacitance. Measurements were then attempted using a CIRCUITMATE Capacitance Meter, but the scales were still not small enough to read the loop capacitance. Therefore, no capacitance measurements appear to be valid.

Loop observations included at least 50 passes of random vehicles each for two, three, four, and five turns of wire. Following each observation, the frequency was measured again. All measurements and observations were then repeated on the 15" deep buried loop.

RESULTS

Bicycles, MOPEDs, and Motorcycles

The 10 inch deep buried loop did not perform as well as expected for these small vehicles. The bicycle and Moped were generally very hard to detect, with 5 turns and a high sensitivity level the only combination producing 100% detection, as shown in Table 1.

One-hundred percent detection includes paths B through J (one foot outside the loop perimeter). It is considered necessary for the bicycle to be detected one foot outside of the loop boundary because that is generally where the bicyclist will ride.

Table 1: % Accurate Detection of Small Vehicles with 10 inch Deep Buried Loop

Number of Turns	Sensitivity Setting	Bicycle	Moped	Motorcycle
Two	Medium	0.0	0.0	0.0
Three	Medium	0.0	0.0	0.0
Four	Medium	20.0	0.0	42.4
Five	Medium	5.6	0.0	78.4
Two	High	0.0	0.0	0.0
Three	High	0.0	0.0	70.4
Four	High	55.6	0.0	100.0
Five	High	100.0	77.8	100.0

If only paths located within the loop perimeter are considered, the MOPED achieved 100% detection on high sensitivity and five turns. However, no MOPED detections occurred on any other number of turns or sensitivity combination.

Much better results were achieved with the motorcycle than the other small vehicles with 100% detection occurring on high sensitivity with both four and five turns of wire. If only paths located within the perimeter are considered, the motorcycle also achieved 100%

detection with five turns and a medium sensitivity and also three turns and high sensitivity. Complete results for all three vehicles are located in Appendices A, B and C.

Figure 4 shows the percent change in inductance the small vehicles achieved. Only the motorcycle had a large enough change in inductance to be detected by both types of detectors on medium sensitivity. The moped and bicycle registered very small percent changes in inductance and are very hard to detect. Complete results are listed in Appendix D.

High Profile Truck

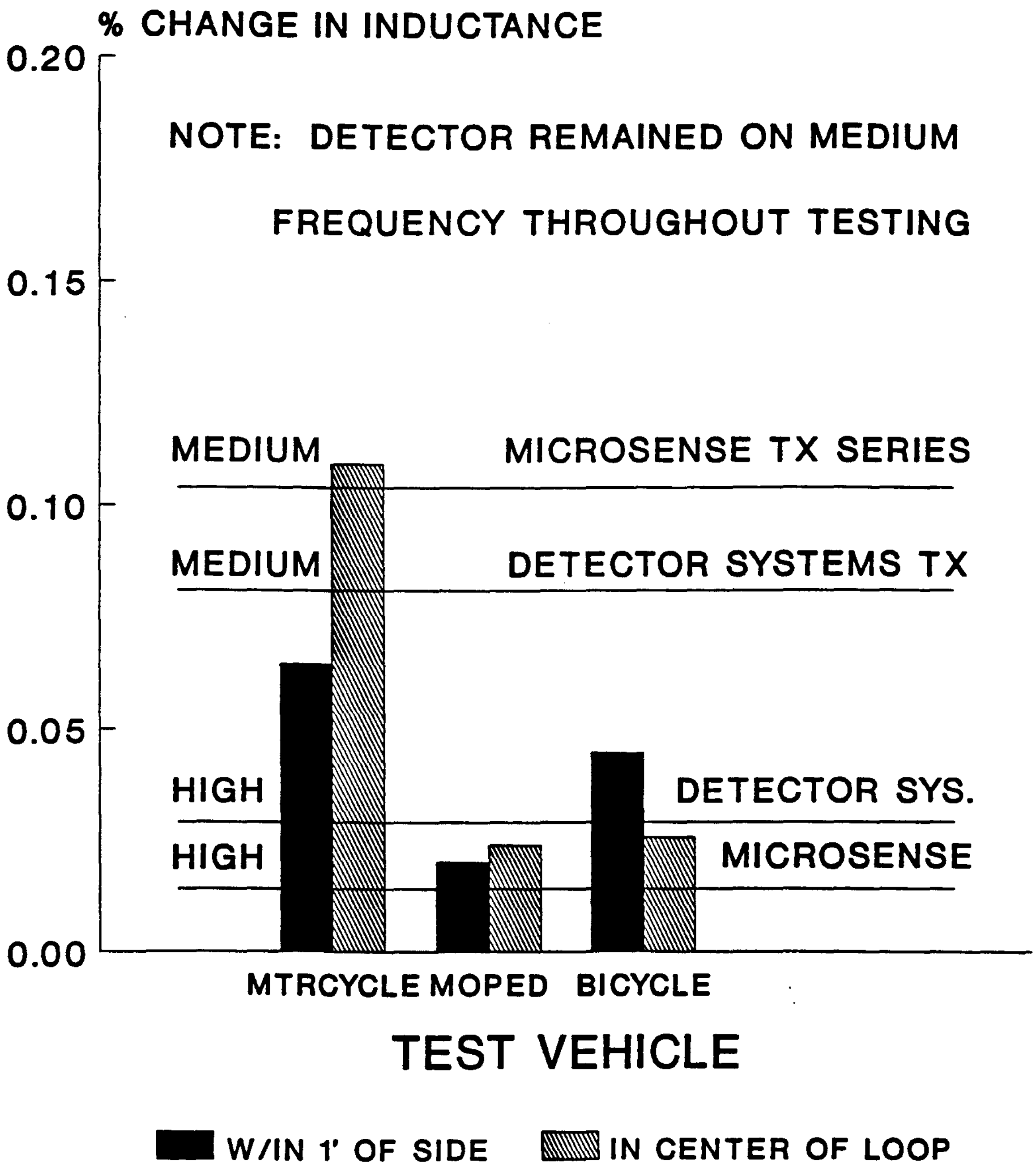
The 15" deep buried loop performed much better than the 20" deep buried loop in detecting high profile trucks. Low sensitivity did not accurately detect the trucks on either loop or on two, three, four, or five turns of wire. On medium and high sensitivity, however, there was a significant difference between the 15" deep loop and the 20" deep loop, as shown in Table 2. The 15" deep loop performed significantly better in all cases except five turns and high sensitivity.

Table 2: % Signal Held of the High Profile Truck

Number of Turns	Sensitivity Setting	15" Deep Loop	20" Deep Loop
Two	Medium	0.0	0.0
Three	Medium	100.0	33.3
Four	Medium	100.0	50.0
Five	Medium	100.0	71.4
Two	High	100.0	50.0
Three	High	83.3	33.3
Four	High	100.0	83.3
Five	High	100.0	100.0

An accurate detection consisted of the detector holding the signal for the entire length of the truck. Many detections showed the presence of two vehicles instead of one truck. Three wire turns and high sensitivity performed questionably on both loops. In

Figure 4: % Shift in Inductance for Small Vehicles



March 1989, during loop installation, construction equipment accidentally cut the third wire of the 15" deep buried loop. An emergency splice on that wire is probably the cause of the questionable results. Due to time constraints, the sample size was smaller than desirable, but the data did present an accurate trend of high profile truck detection.

The frequency measurements taken on many vehicles travelling over the loop indicate a large variation in percent change of inductance between different vehicle sizes and types and within different vehicles, as shown in Figure 5. The water truck was consistently picked up on high sensitivity, sometimes on medium sensitivity, but rarely on low sensitivity. The sample size of frequency was less than desirable for all vehicles except the water truck due to time constraints.

Despite being a large vehicle, a concrete truck caused a lower percent change in inductance than all other vehicles except the Bronco. A large variation in percent inductance change also was noted for the same vehicles. The data do incorporate samples from many of the number of turns from both loops. Complete results of this study are contained in Appendices E and F.

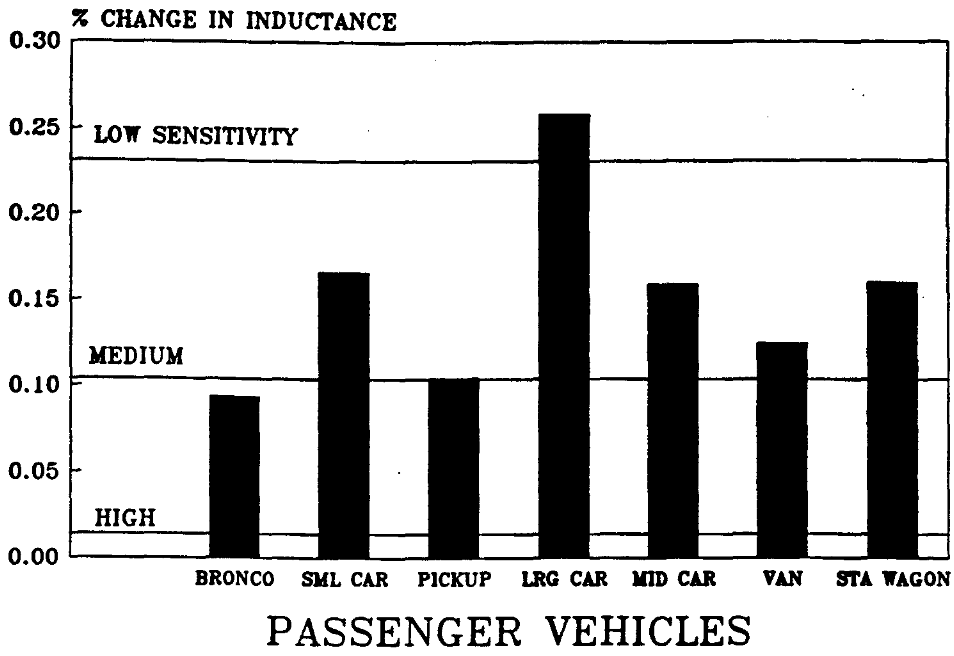
Manhole Sensitivity

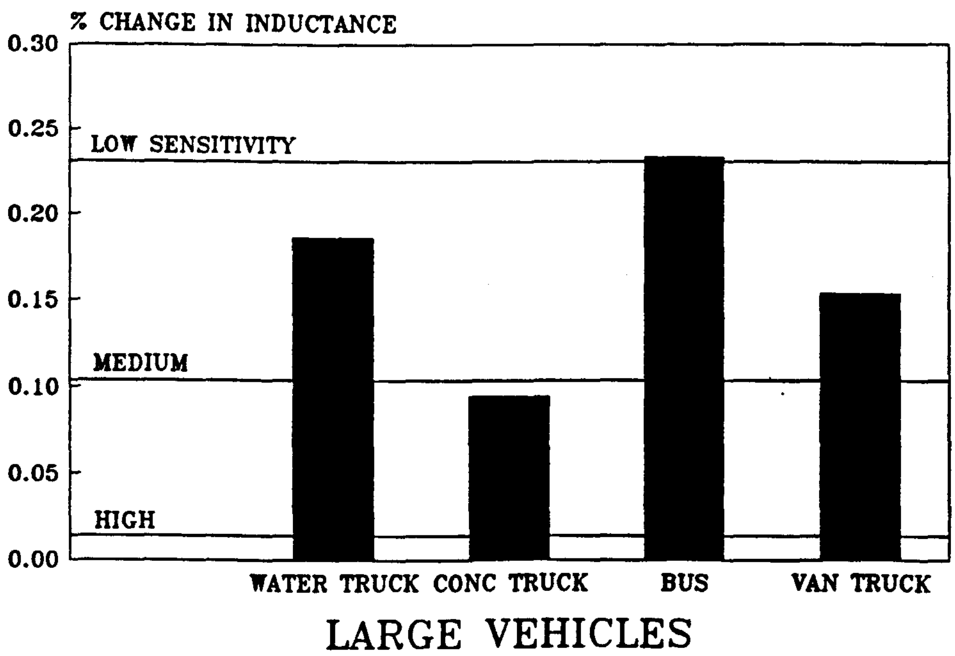
The manhole had virtually no effect on the detection ability of the loop. Two turns of wire on low sensitivity accurately detected 100% of the vehicles. As the number of turns of wire increased, many false detections were recorded from the adjacent lane, as shown in Table 3. With five turns of wire, only 82.3% of

Table 3: Manhole Surface Loop on High Sensitivity

Number of Turns	Percent of Spillovers
Two	0.0
Three	3.4
Four	13.1
Five	17.7

Figure 5: % Shift in Inductance by Vehicle Type for Deep Buried Loops





the detections on high sensitivity were from the right lane, with the other 17.7% of the detections being spillovers. This rate of spillovers is common with loops only 22 inches from the lane line and is not caused by the manhole. Regular surface loops less than two feet from the adjacent lane have a similar percent of false detections. Complete results can be found in Appendix G.

Water Sensitivity

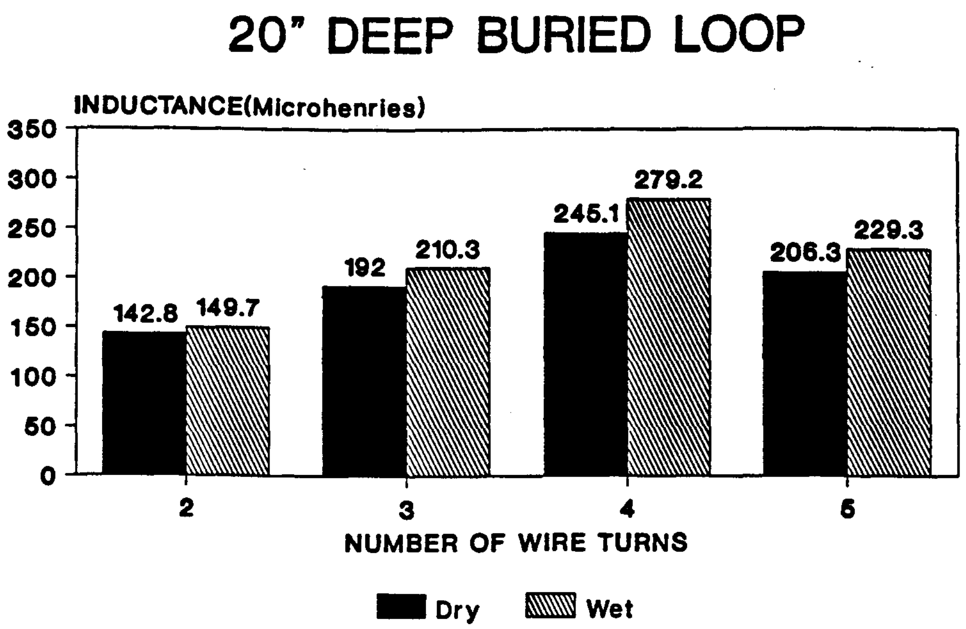
Water had virtually no effect on the detection ability of either the 15 inch or the 20 inch deep buried loops. The inductance did slightly increase, as shown in Figure 5, but the detector unit adjusted and remained very accurate. The only problem in detection accuracy was for two turns of wire and low sensitivity. However, this problem also occurred in the dry condition, so water cannot be considered the cause.

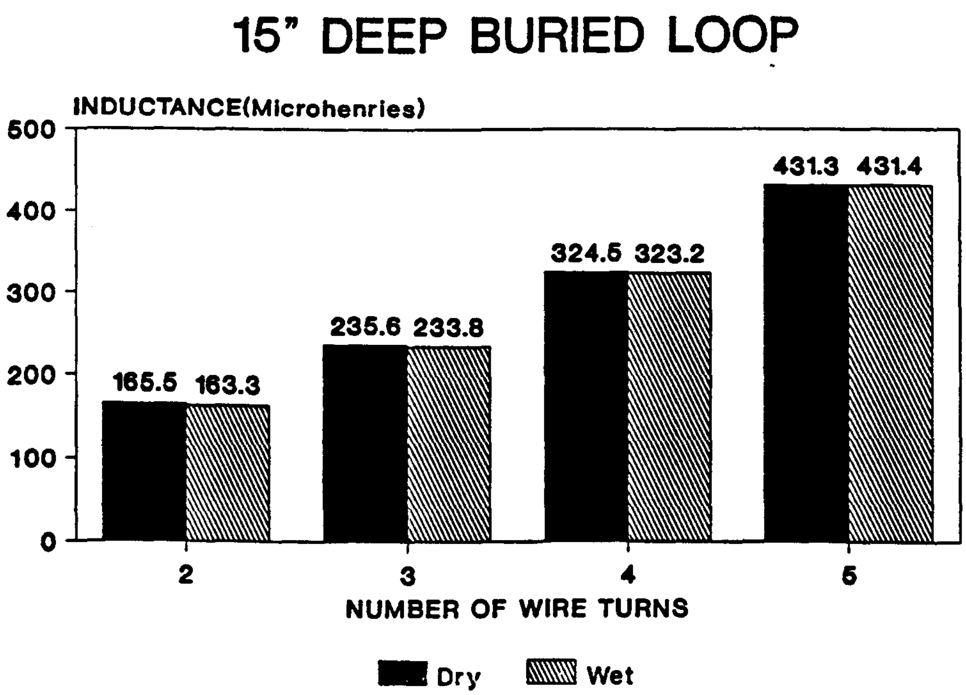
Percent detection accuracy is shown in Table 4 for low sensitivity only. All other sensitivity and number of turn combinations had a 100 percent detection accuracy except medium sensitivity and four turns on the 20" deep loop. In this case, one motorcycle was not detected resulting in a detection accuracy of 97.9%. Complete results are located in Appendices H and I.

Table 4: % Detection of Water Saturated Loop on Low Sensitivity

Number of Turns	15" Deep	20" Deep
Two	61.4	52.6
Three	100.0	94.3
Four	100.0	97.9
Five	100.0	89.8

Figure 6: Wet and Dry Inductance of a Deep Buried Loop





FINDINGS

Deep Buried Loop Recommendations

Deep buried loops are not recommended to be used for bicycle or moped detection. Motorcycle detection is possible with 10" deep buried loops using four or more turns and a high sensitivity. However, spillover effects for a 10" deep buried loop are not known. Therefore, surface loops or deep buried loops much closer to the surface are recommended for use in bicycle, MOPED, and motorcycle detection.

Deep buried loops accurately detect high profile trucks. Any deep buried loop can provide accurate detections up to a maximum depth of 15". For a 15" deep loop, three or four turns of wire with a medium sensitivity setting will achieve 100% detection without any spillover effects if reasonable care is taken to keep the loop edge away from the lane line.

Water and Manhole Comments

Water had virtually no effect on loop detector performance. A slight increase in the inductance did occur between the dry and wet conditions, but the TX series detector was able to adjust. The same detection accuracy resulted in both the dry and wet conditions. It is not worth the added expense to insure that a loop is 100% sealed from water since water has no effect on loop detector accuracy.

The manhole had no effect on the detection accuracy of the surface loop. The loop detected just as well with the manhole as a loop without a manhole. The only consideration to be given when placing a loop near or around a manhole is the amount of maintenance and construction which will occur at the manhole. Damage to the loop by construction equipment should be avoided.

REFERENCES

1. Woods, Donald L., *Documentation Manual - Induction Loop Detector Shape Detection Patterns*, Report 163-3, Texas Transportation Institute, Texas A&M University, College Station, Texas, July 1990.

2. Woods, Donald L., *Texas Traffic Signal Detector Manual*, Report 163-1, Texas Transportation Institute, Texas A&M University, College Station, Texas, February 1991.

3. Federal Highway Administration, *Traffic Detector Handbook, 2nd Edition*, July 1990.

4. Report 163-3, Comments from Mr. Mills, FHWA.

VITA

Robert Alan Hamm was born in Somerville, New Jersey on October 27, 1969. In 1979 he moved to Beaumont, Texas where he attended primary and secondary schools in the Beaumont Independent School District. Robert was graduated from West Brook Senior High School in May 1988.

During the summer of 1990, Robert was employed by the Texas State Department of Highways and Public Transportation. Robert is currently a senior at Texas A&M University and will receive his undergraduate degree in Civil Engineering in August 1992. He is a member of Chi Epsilon, the American Society of Civil Engineers and the National Society of Professional Engineers. Robert is considering attending graduate school following graduation.

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APPENDIX A: BICYCLE TEST DATA

July 30, 1991

10 inch Deep Buried 6' X 6' 45 Degree Skewed Loop
1200 Block Neal Pickett Drive
Detector Systems Digital Loop Detector Model #813-100SS
Medium Frequency Setting

Bicycles Tested:
Cannondale Criterium Series - Aluminum Frame
Diamondback Chromoly Ascent - Serial #7FA5011

THREE WIRE TURNS

SENSITIVITY SETTING	NO DETECTION	DETECTION	PERCENT DETECTION
LOW	-	-	-
MEDIUM	-	-	-
HIGH	9	0	0.00

FOUR WIRE TURNS

SENSITIVITY SETTING	NO DETECTION	DETECTION	PERCENT DETECTION
LOW	-	-	-
MEDIUM	8	2	20.00
HIGH	4	5	55.56

FIVE WIRE TURNS

SENSITIVITY SETTING	NO DETECTION	DETECTION	PERCENT DETECTION
LOW	-	-	-
MEDIUM	17	1	5.56
HIGH	0	31	100.00

APPENDIX B: MOPED TEST DATA

July 31, 1991

10 inch Deep Buried 6' X 6' 45 Degree Skewed Loop
1200 Block Neal Pickett Drive
Detector Systems Digital Loop Detector Model #813-100SS
Medium Frequency Setting

Moped Tested:
1986 Honda Spree Model #NQ50G

FOUR WIRE TURNS

SENSITIVITY SETTING	NO DETECTION	DETECTION	PERCENT DETECTION
LOW	-	-	-
MEDIUM	-	-	-
HIGH	9	0	0.00

FIVE WIRE TURNS

SENSITIVITY SETTING	NO DETECTION	DETECTION	PERCENT DETECTION
LOW	-	-	-
MEDIUM	9	0	0.00
HIGH	12 *	42	77.78

* All 12 were one foot outside of the loop, 6 on path B and 6 on Path J

APPENDIX C: MOTORCYCLE TEST DATA

August 2, 1991

10 inch Deep Buried 6' X 6' 45 Degree Skewed Loop
1200 Block Neal Pickett Drive
Detector Systems Digital Loop Detector Model #813-100SS
Medium Frequency Setting

Motorcycle Tested:
Suzki 300

TWO WIRE TURNS

SENSITIVITY SETTING	NO DETECTION	DETECTION	PERCENT DETECTION
LOW	-	-	-
MEDIUM	-	-	-
HIGH	6	0	0.00

THREE WIRE TURNS

SENSITIVITY SETTING	NO DETECTION	DETECTION	PERCENT DETECTION
LOW	-	-	-
MEDIUM	9	0	0.00
HIGH	8	19	70.37

FOUR WIRE TURNS

SENSITIVITY SETTING	NO DETECTION	DETECTION	PERCENT DETECTION
LOW	-	-	-
MEDIUM	26	19	42.22
HIGH	0	37	100.00

FIVE WIRE TURNS

SENSITIVITY SETTING	NO DETECTION	DETECTION	PERCENT DETECTION
LOW	18	0	0.00
MEDIUM	8	29	78.38
HIGH	0	48	100.00

APPENDIX D: CHANGE IN INDUCTANCE FOR SMALL VEHICLES

July 30, 31, and August 2, 1991
10 inch Deep Buried Skewed Loop - 1200 Block Neal Pickett Drive
Detector Systems Digital Loop Detector Model #813-100SS

NUMBER OF WIRE TURNS	DETECTED OR NOT DETECTED	SENSITIVITY SETTING	VEHICLE TYPE	PATH	INDUCTANCE BASE	INDUCTANCE W/VEHICLE	% CHANGE
4	NOT	MED	CYCLE	A	154.07	154.07	0.000%
4	NOT	MED	CYCLE	B	154.07	154.01	0.039%
4	NOT	MED	CYCLE	B	154.07	154.02	0.032%
4	NOT	MED	CYCLE	C	154.07	153.98	0.058%
4	NOT	MED	CYCLE	C	154.07	154.02	0.032%
4	60%	MED	CYCLE	D	154.07	153.99	0.052%
4	60%	MED	CYCLE	D	154.07	153.99	0.052%
4	20%	MED	CYCLE	E	154.07	153.97	0.065%
4	20%	MED	CYCLE	E	154.07	153.99	0.052%
4	100%	MED	CYCLE	F	154.07	154.00	0.045%
4	100%	MED	CYCLE	F	154.07	153.98	0.058%
4	100%	MED	CYCLE	G	154.07	153.97	0.065%
4	100%	MED	CYCLE	G	154.07	153.97	0.065%
4	100%	MED	CYCLE	H	154.07	153.95	0.078%
4	100%	MED	CYCLE	H	154.07	153.95	0.078%
4	NOT	MED	CYCLE	I	154.07	153.99	0.052%
4	NOT	MED	CYCLE	I	154.07	153.98	0.058%
4	NOT	MED	CYCLE	J	154.07	154.05	0.013%
4	NOT	MED	CYCLE	J	154.07	154.00	0.045%
4	NOT	HIGH	CYCLE	A	154.07	154.07	0.000%
4	100%	HIGH	CYCLE	B	154.07	154.04	0.019%
4	100%	HIGH	CYCLE	B	154.07	154.03	0.026%
4	100%	HIGH	CYCLE	C	154.07	153.99	0.052%
4	100%	HIGH	CYCLE	C	154.07	154.00	0.045%
4	100%	HIGH	CYCLE	D	154.07	153.95	0.078%
4	100%	HIGH	CYCLE	D	154.07	153.99	0.052%
4	100%	HIGH	CYCLE	E	154.07	153.97	0.065%
4	100%	HIGH	CYCLE	E	154.07	153.99	0.052%
4	100%	HIGH	CYCLE	F	154.07	153.97	0.065%
4	100%	HIGH	CYCLE	F	154.07	153.96	0.071%
4	100%	HIGH	CYCLE	G	154.07	153.95	0.078%
4	100%	HIGH	CYCLE	G	154.07	153.97	0.065%
4	100%	HIGH	CYCLE	H	154.07	153.95	0.078%
4	100%	HIGH	CYCLE	H	154.07	153.95	0.078%
4	100%	HIGH	CYCLE	I	154.07	153.99	0.052%
4	100%	HIGH	CYCLE	I	154.07	153.99	0.052%
4	100%	HIGH	CYCLE	J	154.07	154.04	0.019%
4	100%	HIGH	CYCLE	J	154.07	154.03	0.026%
5	NOT	LOW	CYCLE	B	232.72	232.64	0.034%
5	NOT	LOW	CYCLE	B	232.72	232.61	0.047%
5	NOT	LOW	CYCLE	C	232.72	232.51	0.090%
5	NOT	LOW	CYCLE	C	232.72	232.53	0.081%

NUMBER OF WIRE TURNS	DETECTED OR NOT DETECTED	SENSITIVITY SETTING	VEHICLE TYPE	PATH	INDUCTANCE BASE	INDUCTANCE W/VEHICLE	% CHANGE
5	NOT	LOW	CYCLE	D	232.72	232.50	0.095%
5	NOT	LOW	CYCLE	D	232.72	232.52	0.086%
5	NOT	LOW	CYCLE	E	232.72	232.56	0.069%
5	NOT	LOW	CYCLE	E	232.72	232.57	0.064%
5	NOT	LOW	CYCLE	F	232.72	232.50	0.095%
5	NOT	LOW	CYCLE	F	232.72	232.49	0.099%
5	NOT	LOW	CYCLE	G	232.72	232.49	0.099%
5	NOT	LOW	CYCLE	G	232.72	232.48	0.103%
5	NOT	LOW	CYCLE	H	232.72	232.51	0.090%
5	NOT	LOW	CYCLE	H	232.72	232.50	0.095%
5	NOT	LOW	CYCLE	I	232.72	232.51	0.090%
5	NOT	LOW	CYCLE	I	232.72	232.46	0.111%
5	NOT	LOW	CYCLE	J	232.72	232.64	0.034%
5	NOT	LOW	CYCLE	J	232.72	232.64	0.034%
5	NOT	MED	CYCLE	B	232.72	232.59	0.056%
5	NOT	MED	CYCLE	B	232.72	232.64	0.034%
5	100%	MED	CYCLE	C	232.72	232.58	0.060%
5	100%	MED	CYCLE	C	232.72	232.57	0.064%
5	100%	MED	CYCLE	D	232.72	232.48	0.103%
5	100%	MED	CYCLE	D	232.72	232.48	0.103%
5	100%	MED	CYCLE	E	232.72	232.52	0.086%
5	100%	MED	CYCLE	E	232.72	232.50	0.095%
5	100%	MED	CYCLE	F	232.72	232.46	0.111%
5	100%	MED	CYCLE	F	232.72	232.49	0.099%
5	100%	MED	CYCLE	G	232.72	232.46	0.111%
5	100%	MED	CYCLE	G	232.72	232.50	0.095%
5	100%	MED	CYCLE	H	232.72	232.46	0.111%
5	100%	MED	CYCLE	H	232.72	232.48	0.103%
5	100%	MED	CYCLE	I	232.72	232.52	0.086%
5	100%	MED	CYCLE	I	232.72	232.55	0.073%
5	NOT	MED	CYCLE	J	232.72	232.64	0.034%
5	NOT	MED	CYCLE	J	232.72	232.63	0.039%
5	100%	HIGH	CYCLE	B	232.70	232.65	0.030%
5	100%	HIGH	CYCLE	B	232.70	232.63	0.039%
5	100%	HIGH	CYCLE	C	232.70	232.52	0.086%
5	100%	HIGH	CYCLE	C	232.70	232.58	0.080%
5	100%	HIGH	CYCLE	D	232.70	232.48	0.103%
5	100%	HIGH	CYCLE	D	232.70	232.46	0.111%
5	100%	HIGH	CYCLE	E	232.70	232.45	0.116%
5	100%	HIGH	CYCLE	E	232.70	232.44	0.120%
5	100%	HIGH	CYCLE	F	232.70	232.44	0.120%
5	100%	HIGH	CYCLE	F	232.70	232.45	0.116%
5	100%	HIGH	CYCLE	G	232.70	232.44	0.120%
5	100%	HIGH	CYCLE	G	232.70	232.45	0.116%
5	100%	HIGH	CYCLE	H	232.70	232.46	0.111%
5	100%	HIGH	CYCLE	H	232.70	232.45	0.116%
5	100%	HIGH	CYCLE	I	232.70	232.49	0.099%
5	100%	HIGH	CYCLE	I	232.70	232.50	0.095%

NUMBER OF WIRE TURNS	DETECTED OR NOT DETECTED	SENSIT-IVITY SETTING	VEHICLE TYPE	PATH	INDUCTANCE BASE	W/VEHICLE	% CHANGE
5	100%	HIGH	CYCLE	J	232.70	232.60	0.051%
5	100%	HIGH	CYCLE	J	232.70	232.59	0.056%
4	NOT	HIGH	MOPED	B	155.38	155.36	0.013%
4	NOT	HIGH	MOPED	C	155.38	155.35	0.019%
4	NOT	HIGH	MOPED	D	155.38	155.35	0.019%
4	NOT	HIGH	MOPED	E	155.38	155.35	0.019%
4	NOT	HIGH	MOPED	F	155.38	155.35	0.019%
4	NOT	HIGH	MOPED	G	155.38	155.35	0.019%
4	NOT	HIGH	MOPED	H	155.38	155.35	0.019%
4	NOT	HIGH	MOPED	I	155.38	155.35	0.019%
4	NOT	HIGH	MOPED	J	155.38	155.37	0.006%
5	NOT	HIGH	MOPED	B	231.53	231.49	0.017%
5	YES	HIGH	MOPED	C	231.53	231.46	0.030%
5	YES	HIGH	MOPED	D	231.53	231.47	0.026%
5	YES	HIGH	MOPED	E	231.53	231.47	0.026%
5	YES	HIGH	MOPED	F	231.53	231.46	0.030%
5	YES	HIGH	MOPED	G	231.53	231.46	0.030%
5	YES	HIGH	MOPED	H	231.53	231.46	0.030%
5	YES	HIGH	MOPED	I	231.53	231.46	0.030%
5	NOT	HIGH	MOPED	J	231.53	231.50	0.013%
5	YES	HIGH	BICYCLE	B	230.27	230.15	0.052%
5	YES	HIGH	BICYCLE	B	230.27	230.18	0.039%
5	YES	HIGH	BICYCLE	C	230.27	230.15	0.052%
5	YES	HIGH	BICYCLE	C	230.27	230.11	0.069%
5	YES	HIGH	BICYCLE	D	230.27	230.20	0.030%
5	YES	HIGH	BICYCLE	D	230.27	230.20	0.030%
5	YES	HIGH	BICYCLE	E	230.27	230.20	0.030%
5	YES	HIGH	BICYCLE	E	230.27	230.20	0.030%
5	YES	HIGH	BICYCLE	F	230.27	230.23	0.017%
5	YES	HIGH	BICYCLE	F	230.27	230.22	0.022%
5	YES	HIGH	BICYCLE	G	230.27	230.19	0.035%
5	YES	HIGH	BICYCLE	G	230.27	230.19	0.035%
5	YES	HIGH	BICYCLE	H	230.27	230.15	0.052%
5	YES	HIGH	BICYCLE	H	230.27	230.19	0.035%
5	YES	HIGH	BICYCLE	I	230.27	230.10	0.074%
5	YES	HIGH	BICYCLE	I	230.27	230.11	0.069%
5	YES	HIGH	BICYCLE	J	230.27	230.19	0.035%
5	YES	HIGH	BICYCLE	D	230.27	230.20	0.030%
5	YES	LOW	BICYCLE	B	230.40	230.33	0.030%
5	YES	LOW	BICYCLE	C	230.40	230.31	0.039%
5	YES	LOW	BICYCLE	D	230.40	230.31	0.039%
5	YES	LOW	BICYCLE	E	230.40	230.35	0.022%
5	YES	LOW	BICYCLE	F	230.40	230.36	0.017%
5	YES	LOW	BICYCLE	G	230.40	230.35	0.022%
5	YES	LOW	BICYCLE	H	230.40	230.28	0.052%
5	YES	LOW	BICYCLE	I	230.40	230.28	0.052%
5	YES	LOW	BICYCLE	J	230.40	230.34	0.026%

APPENDIX E: HIGH PROFILE TRUCK TEST DATA

July 30, 1991

20 inch Deep Buried 6' X 6' Square Loop
University Drive at Avenue A
Detector Systems Digital Loop Detector Model #813-100SS
Medium Frequency Setting

Truck Tested:
TTI Water Truck - Kenworthy Engine-in-Front Tractor-Trailor Combination

Two Wire Turns

Sensitivity Setting	No Detections	Signal Held	Signal Not Held	% Signal Held
Low	3	0	3 *	0.00
Medium	0	0	6	0.00
High	0	3	3	50.00

Three Wire Turns

Sensitivity Setting	No Detections	Signal Held	Signal Not Held	% Signal Held
Low	-	-	-	-
Medium	0	2	4	33.33
High	0	2	4	33.33

Four Wire Turns

Sensitivity Setting	No Detections	Signal Held	Signal Not Held	% Signal Held
Low	-	-	-	-
Medium	0	3	3	50.00
High	0	5	1	83.33

Five Wire Turns

Sensitivity Setting	No Detections	Signal Held	Signal Not Held	% Signal Held
Low	2	0	1 **	0.00
Medium	0	5	2	71.43
High	0	6	0	100.00

* 1 was detected on both axles and 2 were detected on one axle only
** 1 Axle Only

On five wire turns and high sensitivity, only 1 false detection from the adjacent lane was noted out of 51 random vehicles observed. Thus, spillovers are not a problem for the 20" deep buried loop.

APPENDIX E (CONTINUED): HIGH PROFILE TRUCK TEST DATA

July 30, 1991

15 inch Deep Buried 6' X 6' Square Loop
University Drive at Avenue A
Detector Systems Digital Loop Detector Model #813-100SS
Medium Frequency Setting

Truck Tested:
TTI Water Truck - Kenworthy Engine-in-Front Tractor-Trailor Combination

Two Wire Turns

Sensitivity Setting	No Detections	Signal Held	Signal Not Held	% Signal Held
Low	2	0	0	0.00
Medium	0	0	3	0.00
High	0	6	0	100.00

Three Wire Turns

Sensitivity Setting	No Detections	Signal Held	Signal Not Held	% Signal Held
Low	0	0	3 *	0.00
Medium	0	6	0	100.00
High	0	5	1	83.33

Four Wire Turns

Sensitivity Setting	No Detections	Signal Held	Signal Not Held	% Signal Held
Low	0	1	5	16.67
Medium	0	6	0	100.00
High	0	6	0	100.00

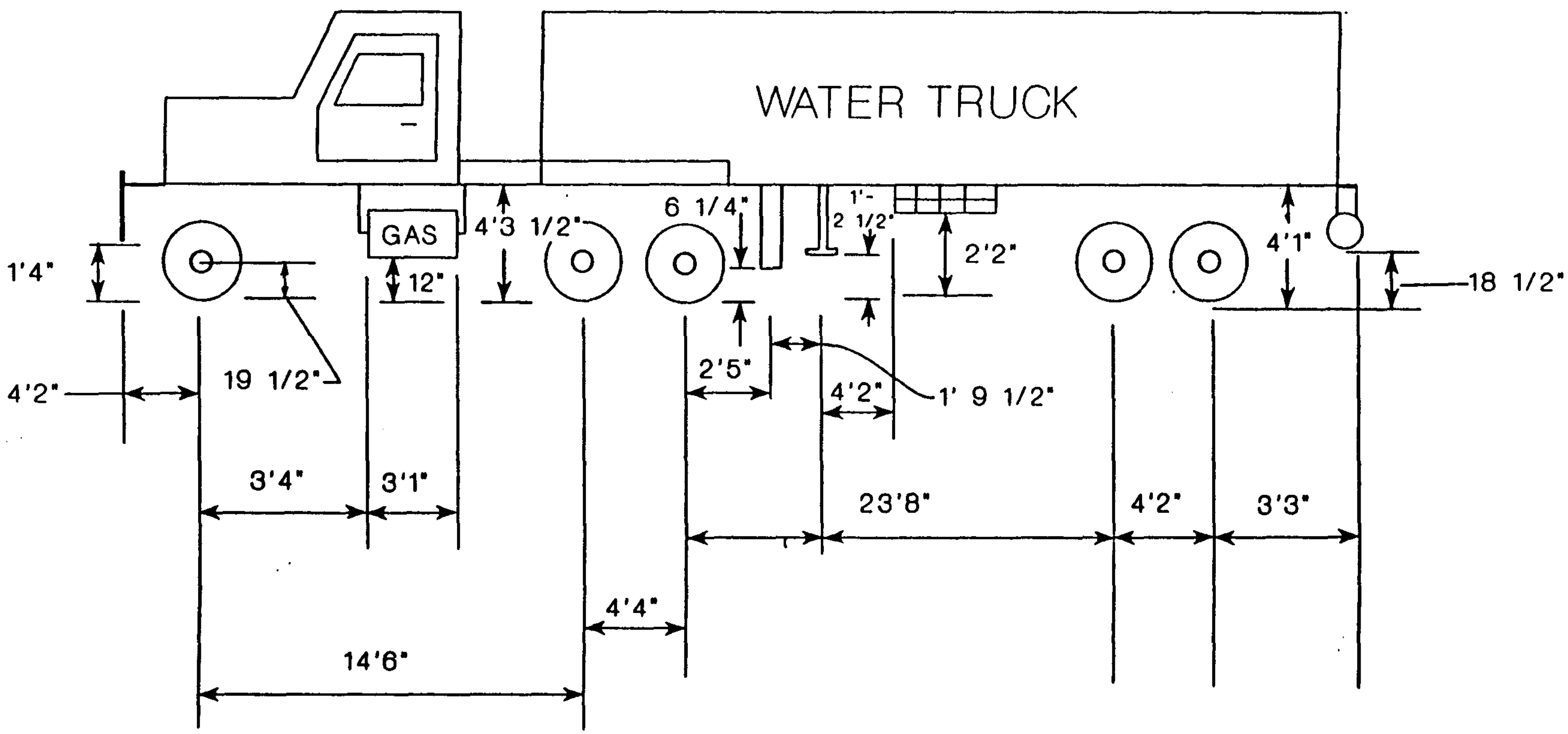
Five Wire Turns

Sensitivity Setting	No Detections	Signal Held	Signal Not Held	% Signal Held
Low	0	1	5	16.67
Medium	0	6	0	100.00
High	0	6	0	100.00

* 2 were detected on one axle only and 1 was detected on both axles

On five wire turns and high sensitivity, only 2 false detections from the adjacent lane were noted out of 57 random vehicles observed. Thus, spillovers are not a problem for the 15" deep buried loop.

KENWORTHY ENGINE - IN - FRONT TRACTOR - TRAILOR COMBINATION



8' WIDE AT FRONT AND BACK

APPENDIX F: CHANGE IN INDUCTANCE FOR TRUCKS AND PASSENGER CARS

July 30, 1991

15" and 20" Deep Buried 6' X 6' Square Loop
University Drive at Avenue A
Detector Systems Digital Loop Detector Model #813-100SS
Medium Frequency Setting
Detector Systems Frequency Tester Model P/N 501

Vehicle Codes:

Number	Vehicle Type	Number	Vehicle Type
0	Bronco/Suburban	6	Large Passenger Car
1	TTI Water Truck	7	Mid-size Passenger Car
2	Small Passenger Car	8	Van
3	Pickup Truck	9	Station Wagon
4	Concrete Truck	10	Van Type Truck
5	Bus		

Number of Turns & Sensitivity Setting	Vehicle Type	Base Inductance	Inductance W/Vehicle	% Inductance Change
15" Loop, 4 Turns, Medium Sens.	7	304.71	303.86	0.2789
	7	304.74	304.06	0.2231
	1	304.71	303.99	0.2363
	2	304.69	304.27	0.1378
	8	304.69	304.19	0.1641
	1	304.64	303.75	0.2921
	1	304.69	303.96	0.2396
	7	304.73	304.26	0.1542
	6	304.73	303.93	0.2625
	1	304.78	304.19	0.1936
	2	304.78	303.70	0.3544
	1	304.76	304.20	0.1838
	1	304.64	303.96	0.2232
	1	304.62	303.86	0.2495
	1	304.62	304.08	0.1773
	1	304.62	303.86	0.2495
	1	304.64	303.93	0.2331
15" Loop, 5 Turns, Low Sensitivity	1	411.58	410.87	0.1725
	7	411.58	410.98	0.1458
	3	411.58	411.03	0.1336
	3	411.58	411.01	0.1385
	7	411.58	410.87	0.1725
	8	411.58	411.33	0.0607
	1	411.61	410.68	0.2259
	1	411.61	410.68	0.2259
	1	411.61	410.73	0.2138
	1	411.61	411.57	0.2527
	2	411.61	410.76	0.2065
	1	411.61	410.90	0.1725

APPENDIX F (CONTINUED): CHANGE IN INDUCTANCE FOR TRUCKS AND PASSENGER CARS

Number of Turns & Sensitivity Setting	Vehicle Type	Base Inductance	Inductance W/Vehicle	% Inductance Change
15" Loop, 5 Turns, Low Sensitivity	10	411.64	410.90	0.1798
(Continued)	8	411.64	411.09	0.1336
	1	411.69	410.73	0.2332
15" Loop, 5 Turns, Medium Sens.	1	411.61	410.73	0.2138
	1	411.64	410.90	0.1798
	2	411.69	410.98	0.1725
	1	411.69	410.73	0.2332
	3	411.61	411.17	0.1069
	1	411.61	410.43	0.2867
	4	411.61	411.03	0.1409
	1	411.61	410.38	0.2988
	5	411.61	410.00	0.3911
	1	411.58	410.76	0.1992
15" Loop, 5 Turns, High Sensitivity	1	411.58	410.76	0.1992
	6	411.66	410.22	0.3498
	1	411.64	410.90	0.1798
	1	411.61	410.82	0.1919
	1	411.61	410.57	0.2527
	1	411.61	410.54	0.2600
15" Loop, 3 Turns, Medium Sens.	7	215.37	214.94	0.1997
	7	215.38	215.05	0.1532
	6	215.37	215.02	0.1625
	1	215.37	214.91	0.2136
	3	215.37	215.08	0.1347
	1	215.37	214.94	0.1997
	1	215.36	214.99	0.1718
	9	215.36	214.87	0.2275
	1	215.36	214.92	0.2043
	10	215.37	215.16	0.0975
	1	215.37	214.94	0.1997
15" Loop, 3 Turns, Low Sensitivity	8	215.37	215.04	0.1532
	1	215.37	214.98	0.1811
	9	215.37	215.05	0.1486
	7	215.37	215.05	0.1486
	2	215.37	215.06	0.1439
15" Loop, 3 Turns, Low Sensitivity	2	215.37	214.95	0.1950
	7	215.37	215.03	0.1579
	1	215.40	215.07	0.1532
	1	215.38	215.07	0.1718

APPENDIX F (CONTINUED): CHANGE IN INDUCTANCE FOR TRUCKS AND CARS

Number of Turns & Sensitivity Setting	Vehicle Type	Base Inductance	Inductance W/Vehicle	% Inductance Change
15" Loop, 2 Turns, Low Sensitivity	3	144.17	144.07	0.0694
	7	144.17	143.96	0.1457
	7	144.17	144.04	0.0902
	1	144.17	143.96	0.1457
	7	144.18	144.06	0.0832
	1	144.19	143.94	0.1734
	2	144.18	144.01	0.1179
	1	144.19	144.00	0.1318
	4	144.19	144.12	0.0485
	0	144.19	143.99	0.1387
	1	144.20	144.03	0.1179
	1	144.20	144.02	0.1248
15" Loop, 2 Turns, Medium Sens.	9	144.20	144.05	0.1040
	1	144.20	143.96	0.1664
	5	144.20	144.09	0.0763
	7	144.19	143.95	0.1664
	0	144.19	144.12	0.0485
	1	144.19	144.07	0.0832
	2	144.19	144.00	0.1318
	8	144.20	144.04	0.1110
	1	144.19	143.96	0.1595
	1	144.20	143.96	0.1664
	1	144.20	143.99	0.1456
	1	144.24	144.02	0.1525
20" Loop, 5 Turns, Medium Sens.	1	234.52	234.19	0.1407
	1	234.52	234.17	0.1492
	2	234.53	234.22	0.1322
	7	234.54	234.22	0.1364
	2	234.54	234.37	0.0725
	1	234.53	234.17	0.1535
	1	234.53	234.27	0.1109
20" Loop, 5 Turns, Medium Sens.	3	234.53	234.36	0.0725
	7	234.53	234.22	0.1322
	1	234.54	234.27	0.1151
	10	234.54	234.27	0.1151
	1	234.53	234.16	0.1578
	3	234.54	234.36	0.0767
	1	234.53	234.20	0.1407
	1	234.53	234.29	0.1023
	1	234.54	234.20	0.1450
	10	234.66	234.14	0.2216
20" Loop, 5 Turns, Low Sensitivity	1	234.65	234.30	0.1492
	1	234.58	234.24	0.1449
	1	234.59	234.16	0.1833

APPENDIX G: MANHOLE SENSITIVITY STUDY TEST DATA

July 26, 1991

6' X 6' Square Temporary Surface Loop
Villa Maria Road between Texas Avenue and Wayside Drive
24" Diameter Manhole Located in Far Right Hand Eastbound Lane
35' West of the Utility Pole directly in front of the
Crafts Etc. Store Entrance at Manor East Mall

Detector Systems Digital Loop Detector Model #813-100SS
Medium Frequency Setting

	2 Turns Low Sensitivity	2 Turns High Sensitivity	3 Turns High Sensitivity	4 Turns High Sensitivity	5 Turns High Sensitivity
Manhole - Vehicle Not Detected	0	0	0	0	0
Manhole - Vehicle Detected	50	50	56	53	51
Adjacent Lane - Total	—	—	—	36	47
Adjacent Lane - Detected	0	0	2	8	11
% Adjacent Lane Detected	0.00	0.00	—	18.18	18.97
% Accurate Detections	100.00	100.00	96.55	86.89	82.26

APPENDIX H: WATER SENSITIVITY TEST DATA - 20" LOOP

July 10, 1991 and July 12, 1991
20 inch Deep Buried 6' X 6' Square Loop
University Drive at Avenue A
Detector Systems Digital Loop Detector Model #813-100SS
Medium Frequency Setting
Randomly Sized Vehicles Tested

TWO WIRE TURNS

SENSITIVITY SETTING	NO DETECTION	SIGNAL HELD	SIGNAL NOT HELD	% SIGNAL HELD
LOW	55	61	0	52.59
MEDIUM	0	66	0	100.00
HIGH	0	63	0	100.00

THREE WIRE TURNS

SENSITIVITY SETTING	NO DETECTION	SIGNAL HELD	SIGNAL NOT HELD	% SIGNAL HELD
LOW	3	50	0	94.34
MEDIUM	0	46	0	100.00
HIGH	0	46	0	100.00

FOUR WIRE TURNS

SENSITIVITY SETTING	NO DETECTION	SIGNAL HELD	SIGNAL NOT HELD	% SIGNAL HELD
LOW	1 *	46	0	97.87
MEDIUM	1 *	46	0	97.87
HIGH	0	41	0	100.00

FIVE WIRE TURNS

SENSITIVITY SETTING	NO DETECTION	SIGNAL HELD	SIGNAL NOT HELD	% SIGNAL HELD
LOW	5 **	53	1 ***	89.83
MEDIUM	0	52	0	100.00
HIGH	0	46	0	100.00

* Motorcycle
** 3 Were Motorcycles
*** High Profile Truck

APPENDIX H (CONTINUED): WATER SENSITIVITY TEST DATA - 20" LOOP

July 10, 1991

Detector Systems Frequency Tester Model P/N 501
Detector Systems Loop Finder Module P/N 502

TWO WIRE TURNS

	BEFORE WATER SATURATION	AFTER WATER SATURATION	AFTER DETECTIONS
FREQUENCY (Hertz)	51,068	51,169	51,454
INDUCTANCE (Microhenries)	142.83	142.27	140.70

THREE WIRE TURNS

	BEFORE WATER SATURATION	AFTER WATER SATURATION	AFTER DETECTIONS
FREQUENCY (Hertz)	44,050	44,075	44,244
INDUCTANCE (Microhenries)	191.97	191.75	190.29

FOUR WIRE TURNS

	BEFORE WATER SATURATION	AFTER WATER SATURATION	AFTER DETECTIONS
FREQUENCY (Hertz)	38,983	39,986	39,105
INDUCTANCE (Microhenries)	245.12	232.98	243.59

FIVE WIRE TURNS

	BEFORE WATER SATURATION	AFTER WATER SATURATION	AFTER DETECTIONS
FREQUENCY (Hertz)	42,489	42,256	42,268
INDUCTANCE (Microhenries)	206.34	208.62	208.50

APPENDIX H (CONTINUED): WATER SENSITIVITY TEST DATA - 20" LOOP

July 12, 1991

Detector Systems Frequency Tester Model P/N 501
Detector Systems Loop Finder Module P/N 502

TWO WIRE TURNS

	BEFORE WATER	AFTER WATER	AFTER DETECTIONS	AFTER 3 DAYS
FREQUENCY (Hertz)	51,068	48,911	49,890	47,585
INDUCTANCE (Microhenries)	142.83	155.70	149.66	164.51

THREE WIRE TURNS

	BEFORE WATER	AFTER WATER	AFTER DETECTIONS	AFTER 3 DAYS
FREQUENCY (Hertz)	44,050	41,539	42,092	39,901
INDUCTANCE (Microhenries)	191.97	215.88	210.25	233.47

FOUR WIRE TURNS

	BEFORE WATER	AFTER WATER	AFTER DETECTIONS	AFTER 3 DAYS
FREQUENCY (Hertz)	38,983	36,495	36,527	33,847
INDUCTANCE (Microhenries)	245.12	279.68	279.19	325.15

FIVE WIRE TURNS

	BEFORE WATER	AFTER WATER	AFTER DETECTIONS	AFTER 3 DAYS
FREQUENCY (Hertz)	42,489	40,299	40,310	38,051
INDUCTANCE (Microhenries)	206.34	229.37	229.25	257.27

APPENDIX I: WATER SENSITIVITY TEST DATA - 15" LOOP

July 15, 1991

15 inch Deep Buried 6' X 6' Square Loop
University Drive at Avenue A
Detector Systems Digital Loop Detector Model #813-100SS
Medium Frequency Setting
Randomly Sized Vehicles Tested

TWO WIRE TURNS

SENSITIVITY SETTING	NO DETECTION	SIGNAL HELD	SIGNAL NOT HELD	% SIGNAL HELD
LOW	17	27	0	61.36
MEDIUM	0	23	0	100.00
HIGH	0	21	0	100.00

THREE WIRE TURNS

SENSITIVITY SETTING	NO DETECTION	SIGNAL HELD	SIGNAL NOT HELD	% SIGNAL HELD
LOW	0	21	0	100.00
MEDIUM	0	18	0	100.00
HIGH	0	20	0	100.00

FOUR WIRE TURNS

SENSITIVITY SETTING	NO DETECTION	SIGNAL HELD	SIGNAL NOT HELD	% SIGNAL HELD
LOW	0	17	0	100.00
MEDIUM	0	21	0	100.00
HIGH	0	16	0	100.00

FIVE WIRE TURNS

SENSITIVITY SETTING	NO DETECTION	SIGNAL HELD	SIGNAL NOT HELD	% SIGNAL HELD
LOW	0	21	0	100.00
MEDIUM	0	18	0	100.00
HIGH	0	18	0	100.00

APPENDIX I (CONTINUED): WATER SENSITIVITY TEST DATA - 15" LOOP

July 15, 1991

Detector Systems Frequency Tester Model P/N 501
Detector Systems Loop Finder Module P/N 502

TWO WIRE TURNS

	BEFORE WATER SATURATION	AFTER WATER SATURATION	AFTER DETECTIONS
FREQUENCY (Hertz)	47,440	47,774	47,767
INDUCTANCE (Microhenries)	165.51	163.21	163.26

THREE WIRE TURNS

	BEFORE WATER SATURATION	AFTER WATER SATURATION	AFTER DETECTIONS
FREQUENCY (Hertz)	39,764	39,911	39,919
INDUCTANCE (Microhenries)	235.58	233.85	233.76

FOUR WIRE TURNS

	BEFORE WATER SATURATION	AFTER WATER SATURATION	AFTER DETECTIONS
FREQUENCY (Hertz)	33,879	33,932	33,947
INDUCTANCE (Microhenries)	324.54	323.52	323.24

FIVE WIRE TURNS

	BEFORE WATER SATURATION	AFTER WATER SATURATION	AFTER DETECTIONS
FREQUENCY (Hertz)	29,390	29,416	29,385
INDUCTANCE (Microhenries)	431.25	430.49	431.40