

1. Report No. FHWA/TX-95/1392-9F	2. Government Accession No.	3. Recipient's Catalog No.	
4. Title and Subtitle EFFECTIVE PLACEMENT OF DETECTORS FOR COMPUTERIZED TRAFFIC CONTROL SUMMARY REPORT		5. Report Date December 1994	6. Performing Organization Code
7. Author(s) Donald L. Woods and Neilon J. Rowan		8. Performing Organization Report No. Research Report 1392-9F	
9. Performing Organization Name and Address Texas Transportation Institute The Texas A&M University System College Station, Texas 77843-3135		10. Work Unit No. (TRAIS)	11. Contract or Grant No. Study No. 0-1392
12. Sponsoring Agency Name and Address Texas Department of Transportation Research and Technology Transfer Office P. O. Box 5080 Austin, Texas 78763-5080		13. Type of Report and Period Covered Final Report: September 1993 - November 1993	
15. Supplementary Notes Research performed in cooperation with Texas Department of Transportation and the U.S. Department of Transportation, Federal Highway Administration. Research Study Title: Effective Detector Placement for Computerized Traffic Control		14. Sponsoring Agency Code	
16. Abstract <p>Freeway management systems are used to reduce freeway traffic congestion problems. A major component of freeway management is the inductance loop detector. This research effort evaluates many aspects of inductance loop detectors in freeway management and computerized traffic signal situations to determine the best placement of detectors for computerized traffic control. This report summarizes the findings and recommendations of the eight studies performed under project 1392.</p> <p>Six major topics related to the inductance loop detector itself were studied: lead-in length, detector spacing, crosstalk, wire type, lag time, and speed measurement accuracy. The results pertaining to this information can be found in Research Reports 1392-1, 2, and 8.</p> <p>The placement of inductance loop detectors were also studied. Proper loop detector placement can effectively reduce delay at isolated intersections, diamond interchanges, ramp meters, HOV-lanes, and arterial streets. The role of inductance loop detectors in freeway management was evaluated. The results pertaining to this information can be found in Research Reports 1392-3, 4, 5, 6, and 7.</p>			
17. Key Words Inductance Loop Detector, Diamond Interchange, Ramp Meter, Computerized Traffic Signals, HOV Lane Monitoring, Speed Traps, Lead Length, Isolated Intersection Signalization, Loop Wire		18. Distribution Statement No restrictions. This document is available to the public through NTIS: National Technical Information Service 5285 Port Royal Road Springfield, Virginia 22161	
19. Security Classif.(of this report) Unclassified	20. Security Classif.(of this page) Unclassified	21. No. of Pages 46	22. Price

**EFFECTIVE PLACEMENT OF DETECTORS FOR COMPUTERIZED
TRAFFIC CONTROL SUMMARY REPORT**

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Research Report 1392-9F
Research Study Number 0-1392
Research Study Title: Effective Detector Placement for Computerized Traffic Management

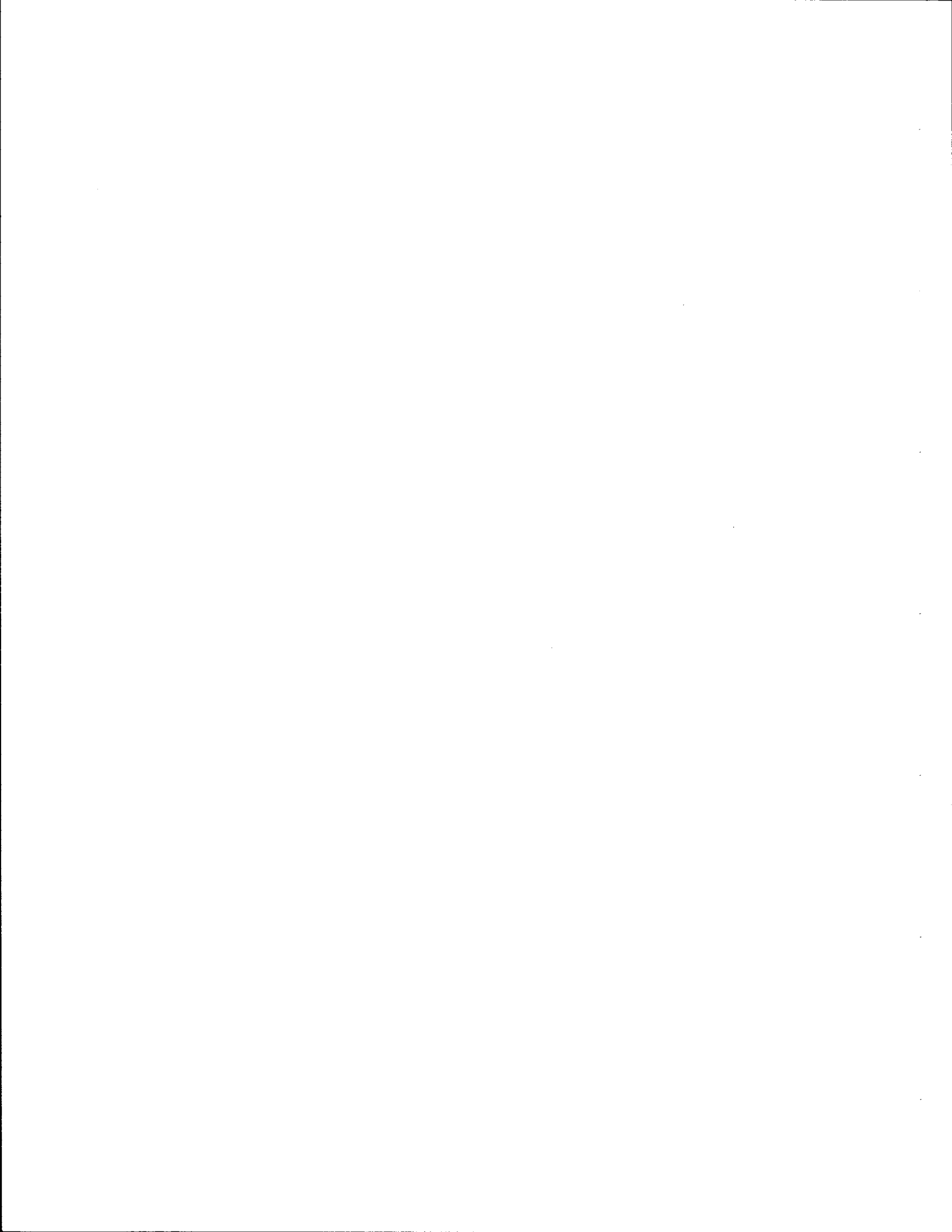
Sponsored by the
Texas Department of Transportation
In Cooperation with
U.S. Department of Transportation
Federal Highway Administration

December 1994

TEXAS TRANSPORTATION INSTITUTE
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College Station, Texas 77843-3135

IMPLEMENTATION STATEMENT

This research provides a better understanding of inductance loop detectors and their application with computerized traffic control systems. This allows a more effective use of induction loop detectors by the Texas Department of Transportation and local governmental units in Texas. The increasing development of freeway management systems demands better information. This research provides practical information on the effective placement of inductance loop detectors for computerized traffic control systems. This report summarizes the major studies performed under project 1392. For questions on the details of this research please refer to the original reports and their authors.



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. 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.

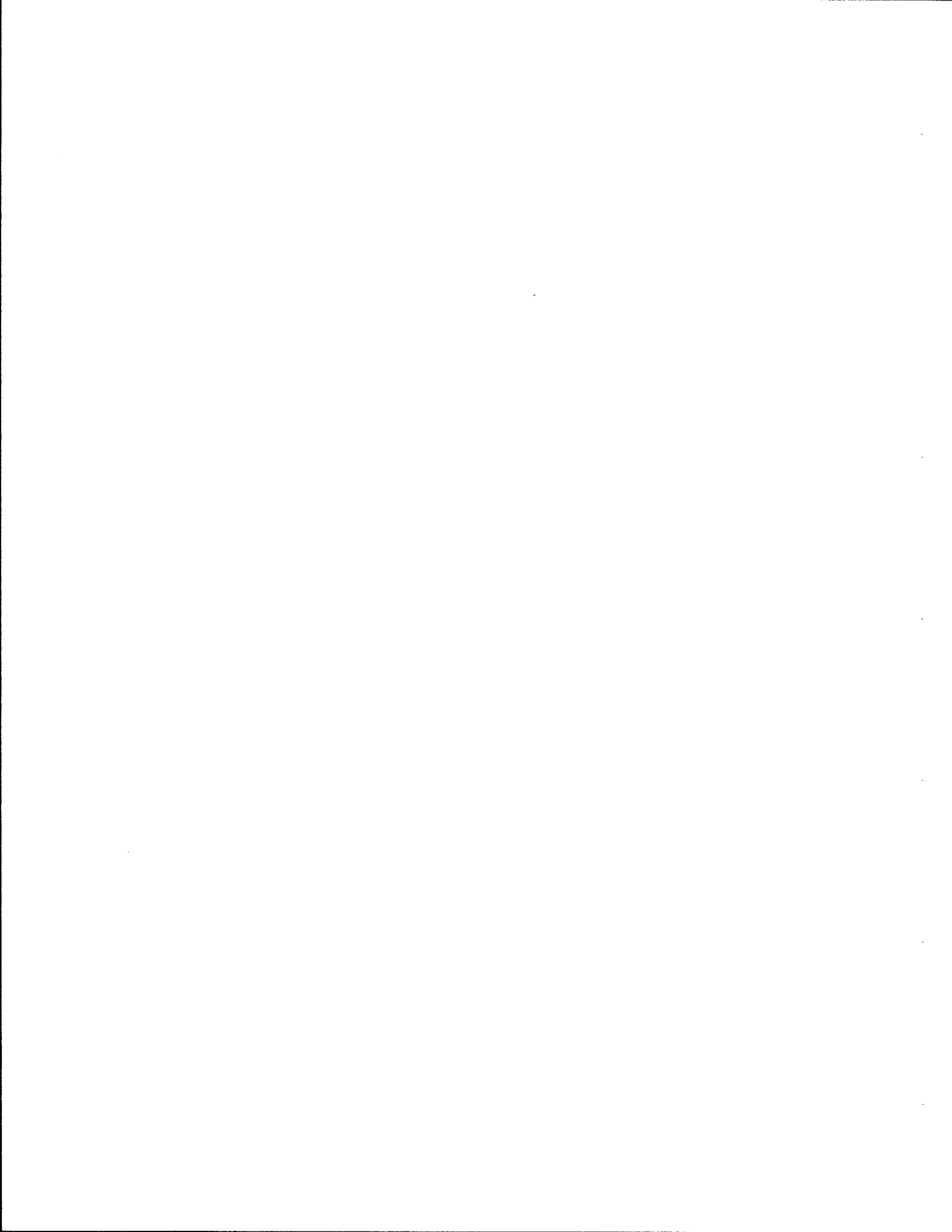


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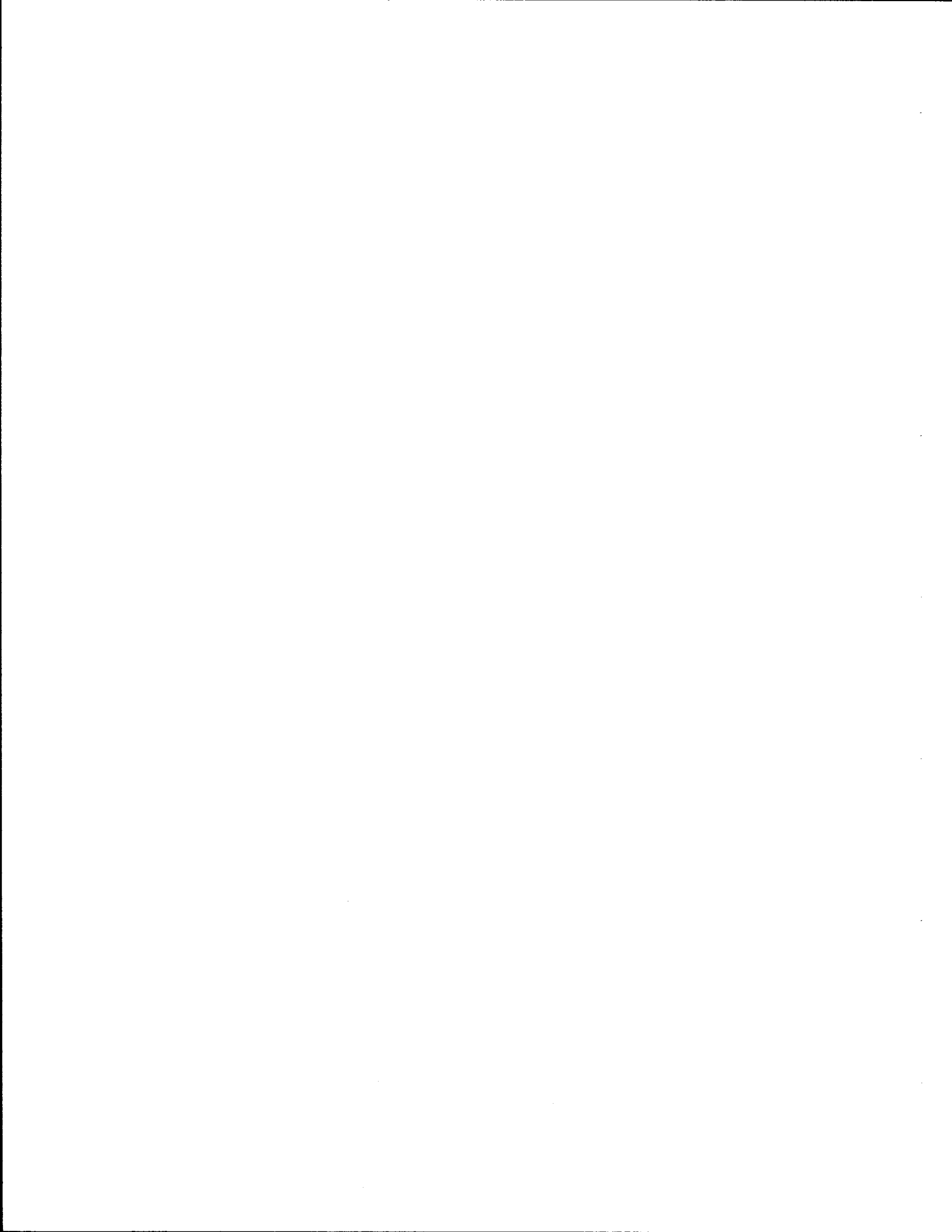
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SUMMARY

Reducing congestion in our urban areas has become a top priority of transportation agencies nationwide. The development and implementation of freeway management systems have begun to ameliorate these problems. Successful freeway management systems are largely dependent upon the availability of factual, dynamic and timely traffic data. Thus, traffic sensors, predominantly the induction loop detectors, have become a major part of the freeway management system. This research effort evaluates various aspects of inductance loop detectors in freeway management systems to determine the optimal or desirable detector system design, installation and operation for computerized traffic control. This report summarizes the findings and recommendations of the eight studies performed under project 1392.

Six major topics related to the inductance the loop detector operation and design are a part of this research. These are: lead-in length, detector spacing, crosstalk, wire type, lag time, and speed measurement accuracy. These items affect the loop detector operation. The detailed results are in reports 1392-1, 2, and 8. Lead-in length up to 1220 meters (4000 feet) is possible. However, a lead-in length of less than 600 meters (1,969 feet) is desirable. No crosstalk between lead-in wires exists for untwisted lead-in wires running in separate saw cuts. Finally, multi-conductor cable is the best wire type for speed measurement. Loops constructed using multi-conductor cable had the least response time and produce the most accurate speed measurement.

Loop detector placement at isolated traffic actuated signals to reduce delay differs from that to increase capacity. A general finding is that loop detector placement can effectively reduce delay at isolated intersections, diamond interchanges, ramp meters, HOV-lanes, and arterial streets. Finally, this research examines the role of inductance loop detectors in freeway management. The detailed results are in reports 1392-3, 4, 5, 6, and 7. When placing detectors at diamond interchange intersections, it is important to provide dilemma zone protection with the detector layout. Spacing between the first two detectors should reflect the 1.2 to 1.5 second passage interval commonly used.



1.0 INTRODUCTION

Project 1392, "Effective Placement of Detectors for Computerized Traffic Control" contains nine different reports. The first eight reports describe certain aspects of the topic. Report number nine summarizes the first eight reports including the major findings and recommendations of each.

The organization of this report is in eight different sections. Each section contains summary information from a 1392 project report. The summary follows the report numbering scheme, should one need to seek more information from the specific reports. The reports numbers and titles are:

- 1392-1 *Inductance Loop Detector Lead-in Length*
- 1392-2 *Inductance Loop Detector Systems Crosstalk*
- 1392-3 *Optimizing Detector Placement for High Speed Isolated Signalized Intersections Using Vehicular Delay as the Criterion*
- 1392-4 *Effective Placement of Detectors at Diamond Interchanges*
- 1392-5 *Distance Requirements for Ramp Metering*
- 1392-6 *Effective Detector Placement for Freeway Management and Computerized Traffic Signal Systems*
- 1392-7 *Optimal Detector Locations for HOV Lane Operations*
- 1392-8 *Speed Measurement with Inductance Loop Speed Traps*

2.0 INDUCTANCE LOOP DETECTOR LEAD-IN LENGTH

2.1 SUMMARY

In freeway management systems, it is frequently necessary to locate inductance loop detectors at great distances from the management center. These remote locations dictate long lead-in wire runs or some alternate transmission system. There is a lack of factual information and general misconceptions regarding the length of lead-in wire that one can use with loop detectors. This phase of the research effort evaluates the use of inductance loop detectors in a freeway environment to determine maximum practical lead-in length.

Lead-in length testing involved five different design vehicles (large and small passenger cars, a pickup truck, a motorcycle, and a high profile truck). Tests involving several different detector units were run. Detection of both passenger cars and the pickup truck was 100 percent with 1220 meters (4000 feet) of lead-in wire. This result held true for all combinations of sensitivity settings and wire loop turns. The detection of the motorcycle and high profile truck depended upon the sensitivity level and wire turns used. Reliable extrapolation of the data show that detection of the passenger vehicles may be possible at distances much greater than 1220 meters (4000 feet). These long lead-in lengths give the designer more flexibility in producing the most functional and cost-effective design.

2.2 RECOMMENDATIONS

The results of these tests provide important insight on the successful use of induction loop detectors on freeways. While the results are not completely conclusive, several trends did develop during the data analysis. The following recommendations provide the transportation engineer with insight into the effective use of induction loop detectors in freeway management.

Lead-in lengths up to 1220 meters (4,000 feet) were tested in this research. Detection of both passenger cars and the pickup truck was 100 percent successful at 1220 meters (4000 feet) at all detector sensitivity levels with 3, 4, 5, and 6 turns of wire. Extrapolation of the data shows that much longer lead-in lengths are possible for detecting passenger cars and pickups. According to these projections, lead-in lengths up to 4270 meters (14,000 feet) with 3 turns of wire and a low sensitivity level may be used successfully. Because of significant limitations in test facilities, no testing of lead lengths of this size was included in the test series. Using higher sensitivity levels and a greater number of wire turns, larger lead-in lengths much longer than the scope of most freeway management systems are possible.

Because long lead-ins can be used with passenger cars, the critical vehicles to consider in design of freeway management systems are motorcycles and high profile trucks. The high profile truck detected well at all lead-in lengths, but typically did not hold the call throughout the length of the truck. This is especially true at the low sensitivity setting. In these instances, the truck is

detected as two vehicles instead of one high profile truck. On medium sensitivity and in the presence mode, maximum lead-in length for detecting the entire truck is greater than 1830 meters (6000 feet). On low sensitivity, maximum lead-in length is between 244 and 915 meters (800 and 3000 feet). Therefore, if the high profile truck is a significant percentage of the freeway traffic stream (say > 10%), use of a medium sensitivity level setting is appropriate. This allows greater flexibility in designing the loop detector systems.

The motorcycle is the most difficult vehicle to detect, primarily due to the square loops in use during testing. Motorcycles are difficult to detect with square loops in normal situations, regardless of the lead-in length. However, successful detections are possible with long lead-in lengths assuming a medium or high sensitivity level. On a medium sensitivity setting, a lead-in length of between 762 and 3,350 meters (2,500 and 11,000 feet) did accurately detect motorcycles, depending on the number of wire turns. Motorcycles do not comprise a large percentage of urban freeway traffic, and therefore, their detection is not a major factor in evaluating freeway conditions.

3.0 INDUCTANCE LOOP DETECTOR SYSTEMS CROSSTALK

3.1 SUMMARY

The crosstalk studies involved extensive research in ways of eliminating crosstalk. Crosstalk is an operational problem. Crosstalk is a situation that exists when two loop detector circuits respond to the same stimulus. Thus, crosstalk results in errant or multiple detections. Four possible areas of crosstalk are:

1. Between loops in adjacent lanes.
2. Between loops in sequence within a lane.
3. Between loop lead-ins on the runs to the controller cabinet.
4. Within the controller cabinet.

This study identified specific conditions when crosstalk can occur.

3.2 RECOMMENDATIONS

The studies in this phase of the research reveal that crosstalk between the lead-in wire, when running in a separate saw cut, and in the cabinet is not a problem. Crosstalk between detectors in adjacent lanes is not a problem for normal lane widths of 3.35 m (11 feet) to 3.6 m (12 feet). Crosstalk between loops in the same lane is a problem when loop spacing is less than 9 meters (30 feet), measured from leading edge to leading edge.

Therefore, the recommendations based on the findings of this phase of the study are:

1. Twist the lead-in wires of each set when two sets of leads run in the same saw cut.
2. Reduce the loop width to 1.5 m (5 feet) when using 3.0-3.35 m (10-11 feet) lanes.
3. Loops placed less than 9 m (30 feet) apart in a lane must operate at frequencies more than 10 KHz apart. This insures that detectors will not crosstalk at any combination of sensitivity and frequency settings.
4. Use shielded lead-in wire for all conduit runs after the first ground box.
5. Maintain a 50 mm (2 inch) minimum separation between lead-in run saw cuts.



4.0 DETECTOR PLACEMENT AT ISOLATED INTERSECTIONS

4.1 SUMMARY

On high speed approaches to isolated intersections, providing for dilemma zone protection may result in sluggish operation and higher delay. A tradeoff analysis of detector placement is, therefore, essential for optimization of dilemma zone protection and reducing delay.

The TEXAS Intersection Simulation Model (Version 3.2) was used to evaluate various detector placement strategies at isolated intersections. The simulations were made for traffic demand ranges of 200 to 800 vph per approach. Mean and 85th percentile speed parameters for the simulation were 90 Km/h (55 mph), 70 Km/h (45 mph), and 55 Km/h (35 mph). Detector placement and spacings for simulation were based on 1.2 to 1.5 second passage intervals for mean and 85th percentile speeds. The 85th percentile speeds were determined as mean speed plus one standard deviation. Dilemma zone coverage was computed using the selected speed parameter, a perception-reaction time of 1.0 seconds, and a deceleration rate of 0.33 g.

At approach volumes less than 500 vph per approach (250 vphpl), a three-detector layout with the first or innermost detector located at the stop bar resulted in lowest delay. There is no significant difference in delay for placements up to 18 meters (60 feet) from the stop bar. At traffic volumes greater than 500 vph per approach (250 vphpl), a three-detector layout with the first detector between 24 meters (80 feet) to 36 meters (120 feet) from the stop bar produces the least delay. This trend appears the same for detector layouts based on mean and 85th percentile speeds.

Regression analyses on delay and cycle length for the different detector layouts have a strong linear relationship. At low approach volumes, there is no effect of mean and 85th percentile speeds on delay. At higher approach volumes, the use of the 85th percentile speed results in a higher delay.

4.2 FINDINGS AND RECOMMENDATIONS

Due to the limitations in the TEXAS Model, simulation of the current TxDOT detector layouts was not possible. Limitations in the number of detectors, lack of special detector functions such as "extended call," "delayed call," "memory function," and "rounded extension intervals" resulted in changing the original study experiment design. New detector layouts based on the dilemma zone criteria for mean and 85th percentile speed were used.

4.2.1 Findings

The following are the findings of this research:

1. For all detector layouts, delay increased with an increase in the approach volume. For volumes below 500 vph (<250 vphpl), detectors closest to the stop bar resulted in lowest delay. At approach volumes greater than 500 vph (> 250 vphpl), a detector layout with the first detector between 24 meters (80 feet) and 36 meters (120 feet) from the stop bar resulted in lowest total delay.
2. For all detector layouts, the cycle lengths increased as approach volumes increased. The detector layout resulting in higher cycle lengths for a particular approach volume and speed produced higher delays.
3. At high operating speed, use of the 85th percentile speed will result in better dilemma zone coverage by the detector system. In turn, this will increase the delay. When high speed conditions exist, a trade-off analysis of detector placement is essential to consider both the dilemma zone risk and the vehicular delay.
4. Regression analyses of delay and cycle length for different detector layouts show that a linear relationship exists between them. For a fully actuated signal control at an isolated intersection, irrespective of approach speed, an estimate of delay per vehicle for a known cycle length is $d = 0.3524C + 0.0028$.
5. Statistical analyses using Duncan's new multiple range test show that delay was not significantly affected by placing the detectors near the stop bar. At higher volumes, delay was not affected by detector layout, when the nearest detector was 24 meters (80 feet) to 36 meters (120 feet) from the stop bar.
6. At low approach volumes, detector layouts for mean or 85th percentile speed will not affect delay or phase length.
7. At high volumes, the extent of space covered by the detectors now plays a dominant role. The simulation results clearly show that as approach volumes increase, the difference in delay also increases for detector layouts based on 85th percentile speed.
8. Using a paired t-test, the effect of speed on delay produced by both the mean and 85th percentile speed-based detector layouts show that at low approach volumes, there is no significant difference in delay. At high approach volumes, delay increases with an increase in approach speed.

9. Table 1 identifies the detector layouts that resulted in lower delay for a particular approach volume and speed.

Table 1. Optimal Detector Layouts, by Approach Volume and Speed

Speed Km/h (mph)	Detector Location from the Stop Bar, m (ft)			
	Mean		85th percentile	
	Volume ≤ 200 Vphpl	Volume ≥ 200 Vphpl	Volume ≤ 200 Vphpl	Volume ≥ 200 Vphpl
90 (55)	12, 70, 125 m (40, 225, 410 ft)	30, 75, 120 m (100, 250, 400 ft)	0, 75, 150 m (0, 250, 500 ft)	30, 90, 150 m (100, 300, 500 ft)
70 (45)	0, 45, 90 m (0, 150, 300 ft)	30, 55, 90 m (100, 200, 300 ft)	0, 50, 105 m (0, 175, 350 ft)	30, 75, 120 m (100, 250, 400 ft)
55 (35)	12, 35, 60 m (40, 115, 190 ft)	24, 45, 70 m (80, 155, 230 ft)	15, 45, 75 m (50, 150, 250 ft)	30, 55, 90 m (100, 200, 300 ft)

4.2.2 Recommendations

4.2.2.1 Practical Engineering Recommendations

When using multiple loop detector layouts on high-volume high speed approaches, any detector located at or close to the stop bar must be disabled after the initial dispersion of the queue following the onset of green. This reduces total intersection delay.

4.2.2.2 TEXAS Model Recommendations

1. The TEXAS Model output consisted only of the number of "max-outs" and "gap-outs". The exact time at which a gap-out occurred or the cause for the gap-out was not available. Hence, it is desirable to include these features in future model enhancements, thereby simulating more accurately real life situations.
2. The scan interval in the NEMA Controller of the TEXAS Model should be 0.1 seconds.

With this capability, the signal timing parameters can be input into the TEXAS Intersection Simulation Model in one-tenths of a second as set in the controller unit.

3. The limitation on the number of detectors in the TEXAS Model (with NEMA controller functions) should be increased to at least 25.
4. Modification of the TEXAS Model (NEMA Controller) should allow presence mode of operation with phase memory detection "off."

5.0 DIAMOND INTERCHANGE DETECTOR SPACING

5.1 SUMMARY

This phase of the research effort was conducted to determine the most effective placement of detectors at diamond interchange intersections. The minimization of delay was the objective function.

Using the Texas Diamond Simulation Model, a study of the placement of detectors on the approach roadways is possible. In particular, the location resulting in the least total interchange delay is the objective. The findings suggest that the first detector location should be about 30 meters (100 feet) back from the stop bar. The length of the detector coverage zone is a function of the distance required to stop at a reasonable deceleration rate (that is, 2.4 m/s^2 [8 fps^2]) and a one second perception reaction time. Intermediate detectors are spaced as necessary to obtain a 1.1 to 1.2 second passage interval between detectors. The resulting detector layout reduces total interchange delay while keeping the dilemma zone to a minimum.

5.2 CONCLUSIONS AND RECOMMENDATIONS

The scope and context of the conclusions and recommendations of this study are based on the TEXAS Diamond Simulation Model. The diamond controller and detectors in the TEXAS Model are in accordance with the 1982 specifications of the TxDOT diamond interchange controller unit. Further, these conclusions and recommendations are limited on the basis of the specific interchange geometry, traffic volume levels, and turning percentages on the arterial and frontage road approaches.

5.2.1 Conclusions

The following are the conclusions of this study:

1. For both "Figure 3" and "Figure 4" (Figures 1 and 2) operations, short advance detector setback distances on frontage roads result in lower interchange delay.
2. The performance of the detector layouts with 15 meters (50 feet) and 30 meters (100 feet) advance detector setback are the same as those in "Figure 3" type operation.
3. At moderate volume conditions (200 vphpl), the detector layout with 30 meters (100 feet) advance detector setback distance on frontage roads is marginally better than the other detector layouts. This applies for total interchange delay for "Figure 4" type operation. However, at high volume conditions (400 vphpl or more), there

is a significant difference in the performance of the detector layout in comparison with other detector layouts.

4. A setback of 30 meters (100 feet) from the stop line is the optimal location for the advance detector on frontage roads for the "Figure 4" phasing sequence, with or without U-turn lanes being present.
5. For "Figure 4" operation, with a transfer gap of 1.5 seconds, the interchange delay is lower than the situation using a 2.5 second transfer gap. This is primarily because of a shorter cycle length.
6. The total interchange delay is more sensitive to U-turn volume than the total approach volume for the "Figure 4" phasing sequence.

5.2.2 Recommendations

Optimal detector layout on frontage roads at a diamond interchange includes a 12 meter (40 feet) long loop located at the stop line and a 1.8 meter (6 feet) long advance detector at 30 meters (100 feet), respectively (Figure 3). Layout 1 provides minimum coverage, and layout 2 provides dilemma zone coverage. Use presence mode operation of both detectors to reduce total interchange delay. The transfer gap for use in "Figure 4" operation should be based on the difference between the maximum saturation headway at the interchange and the loop presence time.

The limitation in the TEXAS Model on the number of detectors that may be used prevents a more detailed study of detector placement strategies at diamond interchanges. Current multiple loop detector placement strategies of the Texas Department of Transportation cannot be simulated due to this limitation. Therefore, it is recommended that further study be conducted to evaluate detector placement at diamond interchanges with multiple loop detection layouts. Recommendations for improving the TEXAS Diamond Simulation Model include eliminating the limitations above.

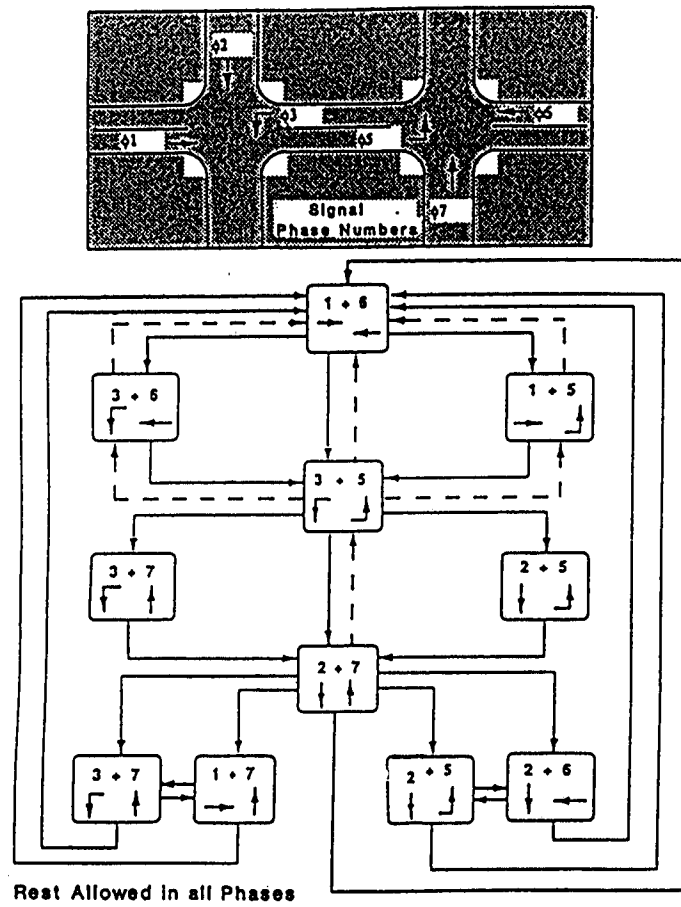


Figure 1. "Figure 3" Phasing Sequence

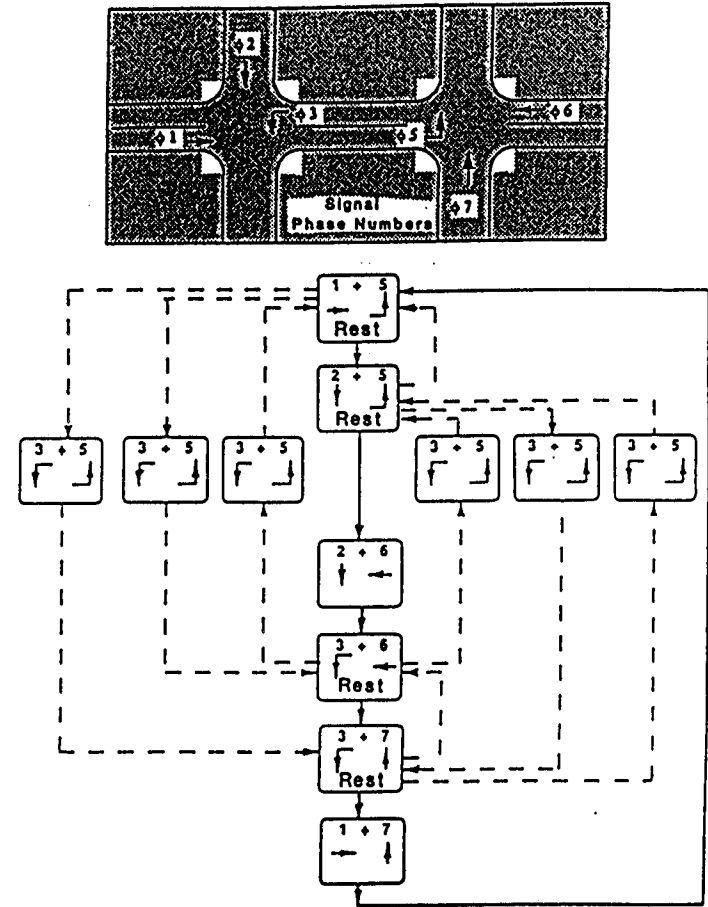


Figure 2. "Figure 4" Phasing Sequence

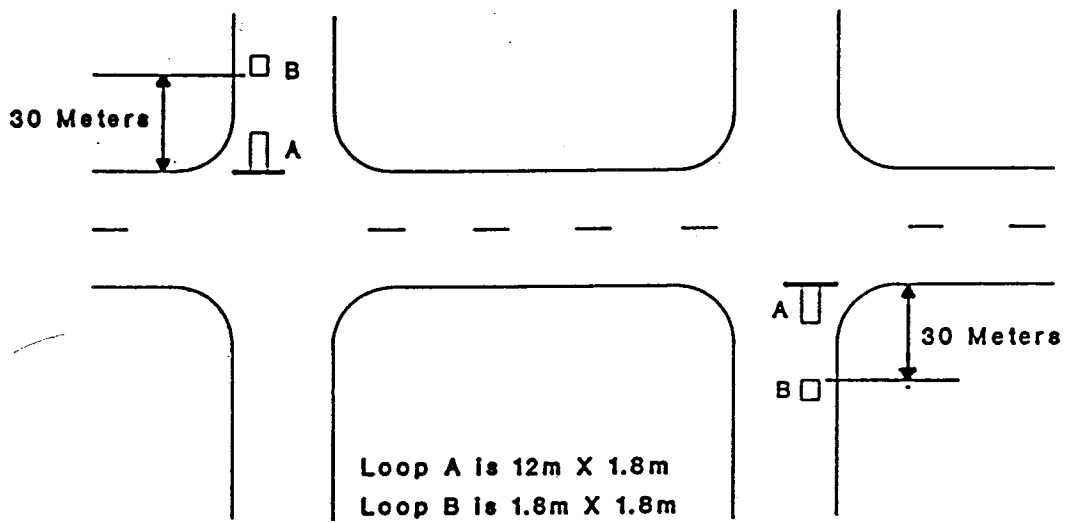


Figure 3. Recommended Detector Placement for the Frontage Road Approach at Diamond Interchanges

6.0 DISTANCE REQUIREMENTS FOR RAMP METERING

6.1 SUMMARY

Several Texas cities are installing ramp metering systems to reduce freeway congestion. This section describes the distance criteria for implementing ramp metering systems on entrance ramps for urban freeways. It outlines a methodology for determining the distance requirements for ramp metering for a wide range of traffic volume and freeway geometric conditions. It presents guidelines for optimally placing the ramp meter traffic signals for specific geometric conditions with a description of the trade-offs one must consider.

Using operational design criteria as a base, procedures to determine the distance requirements for a wide range of freeway merging operations and queue storage conditions are identified. Distance requirements for freeway merging use constant acceleration models of linear motion. Queue storage requirements use a queue storage model. An illustrative example describes the use of the design criteria and how to apply the design criteria for various traffic volume and freeway geometric considerations.

6.2 ILLUSTRATIVE EXAMPLE

Goal: To determine the best placement of a ramp metering system to optimize both the acceleration and storage distances.

- Assumptions:**
- Peak hour traffic conditions.
 - 3-lane frontage road leaving the diamond interchange.
 - Far left lane of the frontage road becomes the entrance ramp.
 - Direct entry type entrance ramp.
 - Entrance lane width = 4.9 m (16 feet).
 - Ramp meter signal placed 1.2 m (4 feet) away from the edge of the entrance ramp travel lane.
 - The Roadside safety clear zone requirement stipulates at least a 9 m (30 foot) clear zone from the edge of the freeway travel lane.

I. Geometric Conditions:

- A. Freeway Speed = 90 km/h.
- B. Angle of Merge = 3 4 X 5 degrees.
- * C. Separation between travel lane and left frontage lane (edge-to-edge) = 18 m.

- D. Length of Entrance Ramp = 260 m.
- E. Merging Distance Available = 150 m.
- F. Storage space available beyond diamond interchange to the start of the entrance ramp = 245 m.
- G. The roadside safety clear zone requirement stipulates at least a 9 m (30 ft) clear zone from the edge of the freeway travel lane.

II. Operational Conditions:

- A. Peak Hour Arrival Rate = 650 vph.
- B. Minimum Metering Rate = 200 (200 vph).
- C. Select cycle length of upstream diamond interchange to be considered:
 2 Minute Time Period _____
 4 Minute Time Period X (To account for overflow queue).
- D. Choose acceptable delay in minutes for queued vehicles which will not lead to frequent violations of the ramp meter signal
 1 _____ 2 _____ 3 X 4 _____ 5 _____ Minutes.

III. Procedure For Placing the Ramp Metering System

- A. The design must allow ample merging distance so the vehicle may achieve a 1.5 second headway after reaching freeway speed and before merging with the freeway travel lane. The merging distance requirement is shown in Figure 2. For a freeway design speed of 90 km/h (55 mph), the minimum merging distance to achieve this headway before entering the through freeway travel lane is 179 m (587 feet).

Merging Distance Required Before Entering the Through Freeway Travel Lane - 179 m (I.).

If the merging distance (I.) is greater than the merging distance available (I.E.), extending the merging lane pavement markings to provide more distance to achieve a 1.5 second headway is necessary. If geometric considerations limit this manipulation of the lane lengths or if the resulting extension ends too close to the next ramp entrance, relocation of the ramp further downstream is a consideration.

- B. Based on the freeway speed, determine the minimum **ramp distance** requirement for acceleration purposes. Calculate this value by considering an acceleration rate of 4.8 Km/h/s (3 mph/s or 4.4 fps/s). For a freeway design speed of 90 km/h (55 mph), the minimum ramp distance to accelerate to freeway speed before entering the merging area is 104 meters (340 feet).

Ramp Distance Which is Necessary for Acceleration Purposes 104 m (ii.).

- C. Measure 9 m (30 feet) from the edge of the freeway travel lane to the left edge of the ramp lane and mark the corresponding point on the ramp. This point gives the available ramp distance for acceleration purposes. If this distance is greater than the minimum necessary distance for acceleration found in III.B. (ii.), select this point for the ramp metering signal; otherwise continue to allocate (I.) the ramp length for acceleration purposes.
- D. The distance from the downstream intersection to the ramp metering signal is available for queue storage. This distance is the queue storage distance available (I.F.). Determine the queue storage length necessary for the given peak hour traffic conditions, metering rate, and the analysis period by using Figures 3 and 4. If the queue storage length necessary is less than the queue storage distance available (I.F.), the design for the ramp metering system is acceptable. Otherwise, the relocation of the ramp metering signal to a point that still meets the minimum ramp distance for acceleration purposes (104 m for freeway speed of 90 km/h [55 mph]) is necessary.
- E. The compromise between the queue storage distance and the roadside safety clear zone requirements (9 meters (30 feet)) depends on the engineer-in-charge of the project. It also depends on the flexibility of the system to shift the pavement markings on the ramp to adjust the clear zone distance.
- F. Figure 8 displays the results of the example problem.

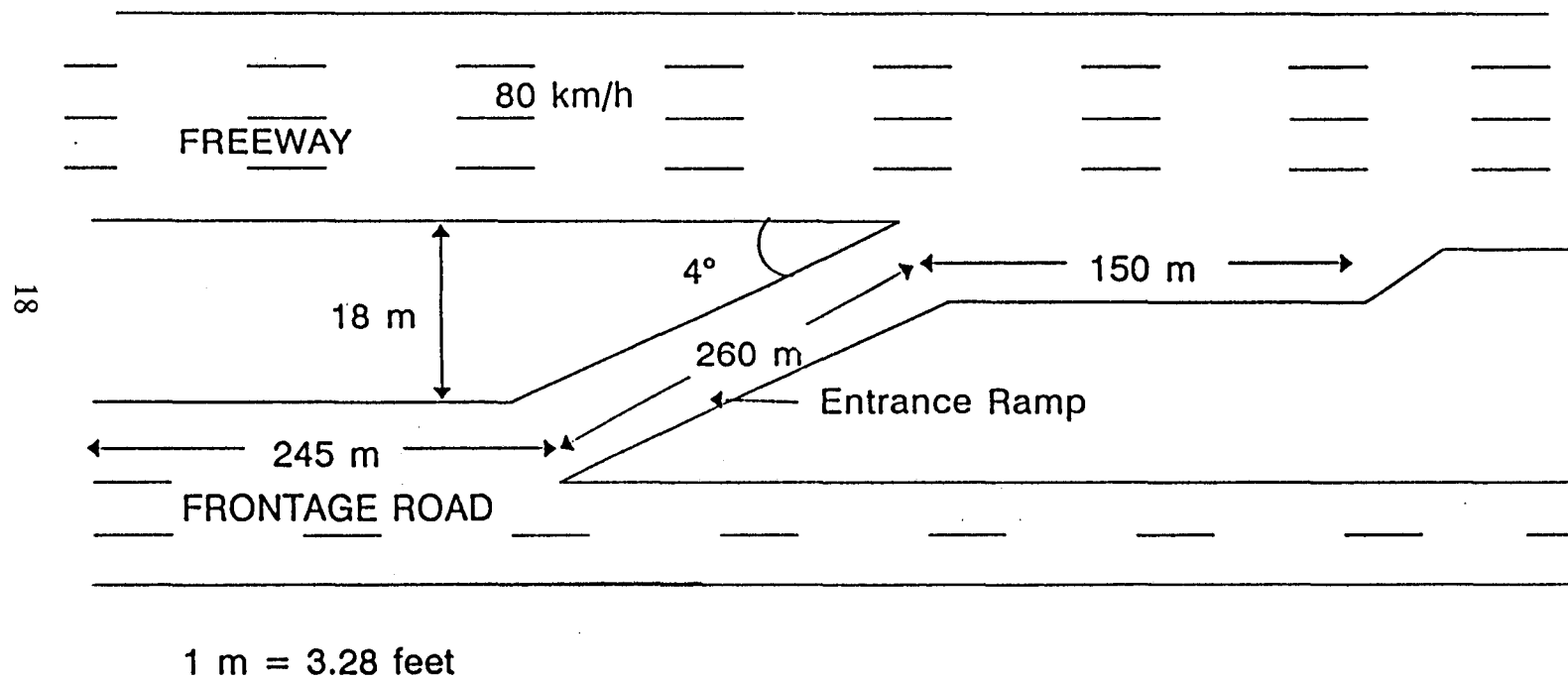


Figure 4. Illustration of Sample Problem

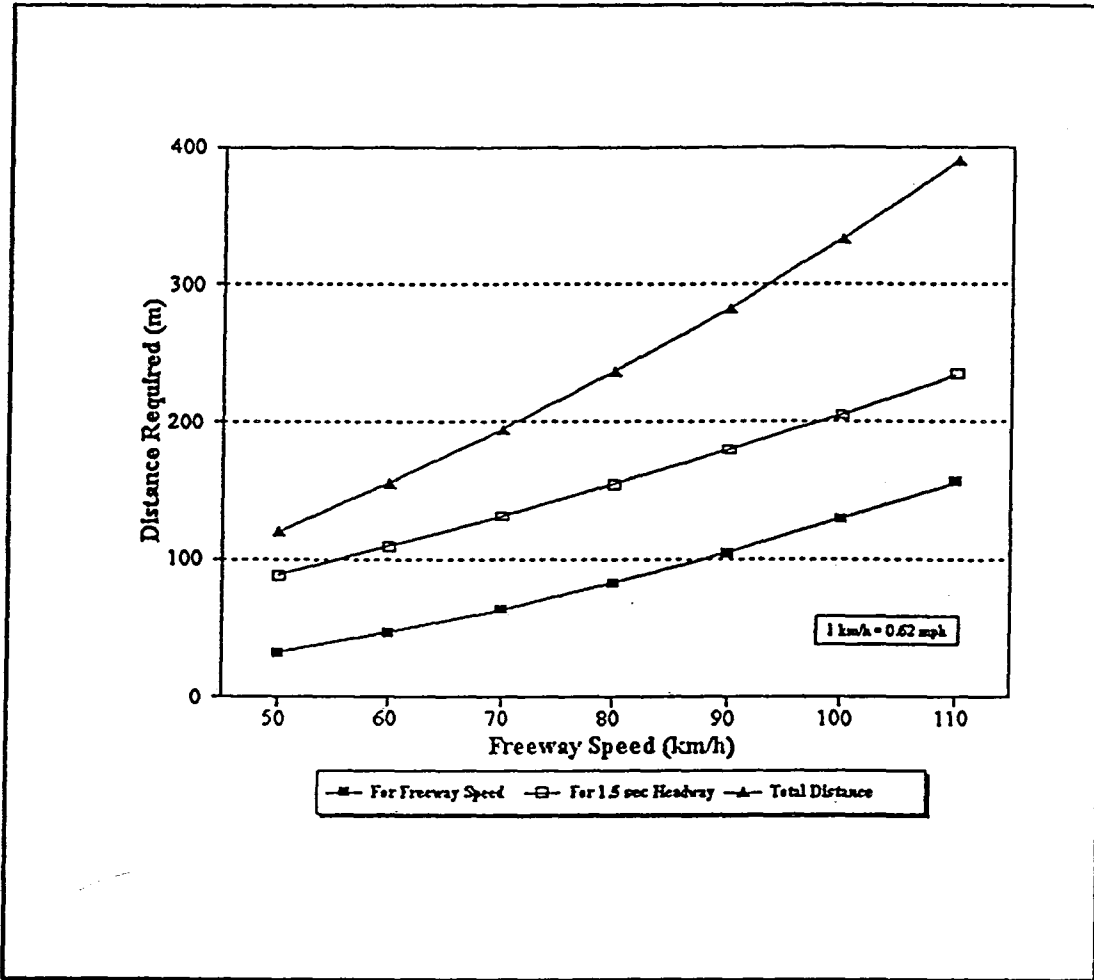


Figure 5. Distance Requirements for the Freeway Merging Operation.

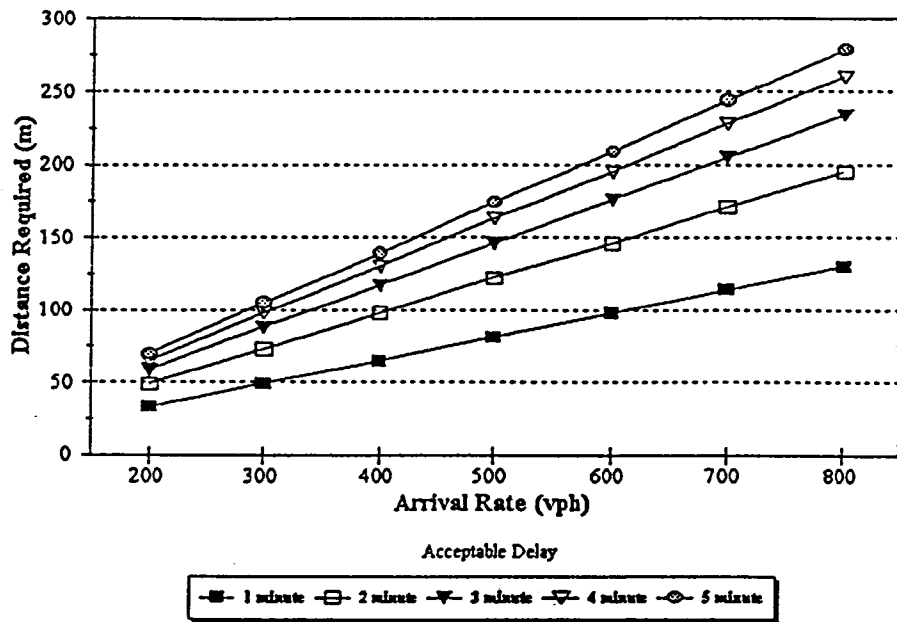


Figure 6. Distance Required for Queue Storage: Two Minute Time Period

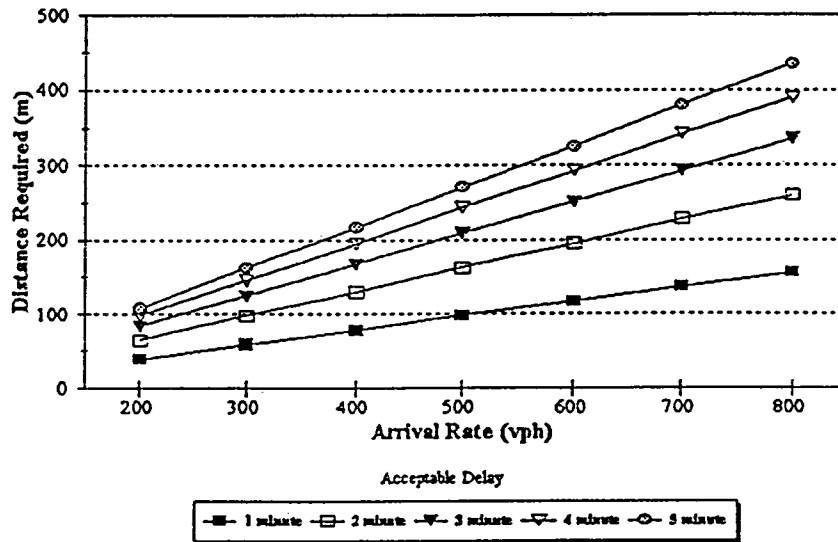
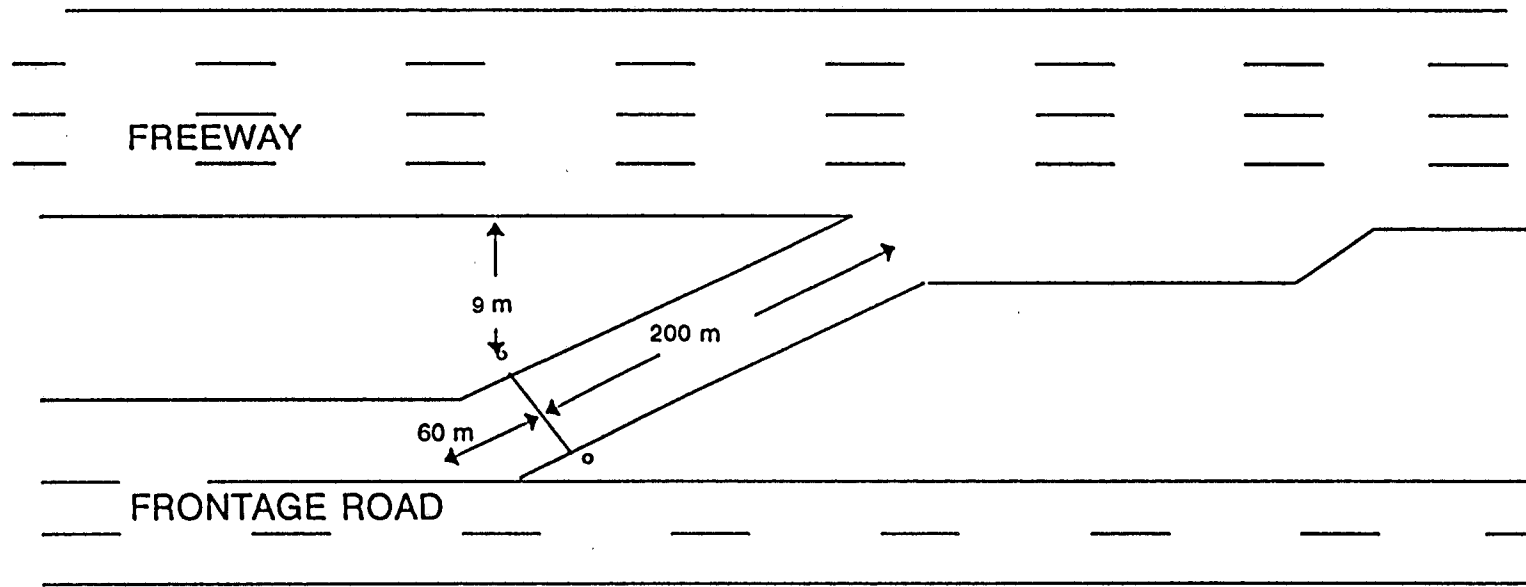


Figure 7. Distance Required for Queue Storage: Four Minute Time Period



1 m = 3.28 feet

Figure 8. Ramp Meter Signal Location

7.0 FREEWAY TRAFFIC MANAGEMENT AND COMPUTERIZED ARTERIAL STREET SIGNAL SYSTEMS

7.1 FREEWAY TRAFFIC MANAGEMENT

7.1.1 Summary

This phase of the research effort uses a benefit/cost approach to determine the optimal spacing of monitoring stations for freeway management. The primary objective function is the cost of the added delay while the queue extends upstream to the next monitoring site. The cost includes all installation and maintenance costs for the monitoring station. The delay costs are those currently in use in the TxDOT HEEM model.

7.1.2 Conclusions and Recommendations

Using the B/C approach results in a break-even situation for monitoring station spacings of 800 meters (2,625 feet) to 1,400 meters (\approx 4,600 feet), depending upon the demand and lane blockage situation one assumes. The longer spacings are for lower demand levels. Since freeways have rather heavy volumes when freeway management is a consideration, the spacing of 800 meters (2,625 feet) deserves serious consideration as the general policy for statewide application.

7.2 COMPUTERIZED ARTERIAL STREET SIGNAL SYSTEMS

7.2.1 Summary

The computerized arterial street signal system differs from the freeway traffic management system in two significant ways. First, major changes in flow occur on the arterial system at more closely spaced points. Second, the adaptation to an identified incident on the arterial street system takes 3 to 4 minutes. For these reasons, monitoring stations along the arterial are more closely spaced.

7.2.2 Conclusions and Recommendations

Using the general benefit/cost procedure discussed above, the average spacing of 800 m (about $\frac{1}{2}$ mile) is the optimal spacing. In the preparation of the B/C analysis cost information, a very important fact came to light. The cost of the monitoring station installation in the field at all potential monitoring site locations is much cheaper than the studies necessary to collect and analyze the data to determine the best monitoring sites.

Based on this finding, a systematic method of reviewing and selecting potential monitoring sites is a major element of Report 1392-6. The general guidelines for arterial streets monitoring

sites are listed below. Monitoring sites should be located:

1. At a spacing of approximately 0.8 Km (about ½ mile) apart, on the average.
2. Up and down stream for each major traffic generator.
3. Up-stream and down-stream from each major intersection.
4. In an area away from driveways.
5. Beyond the acceleration area of up-stream intersections.
6. Beyond the queue storage space for down-stream intersections
7. In a sound pavement area.

Using these general guidelines, a group of potential monitoring sites should be selected. All sites should be instrumented. While only one lane of instrumentation is necessary at each site, multiple lane instrumentation provides redundancy in case of an equipment failure. After the sites are on-line, the correlations of upstream demands with downstream traffic problems are relatively easy to perform. Only those instrumented sites needed in traffic control decisions are left on-line.

8.0 OPTIMAL OPERATION OF HOV LANE FACILITIES

8.1 SUMMARY

To operate efficiently, HOV facilities require several subsystems. Two of these are the HOV mainline monitoring subsystem and the wrong-way detection and monitoring subsystem. Considering the requirements of these two subsystems and the findings of other phases of this research program, recommendations are made for the placement and design of HOV lane detection subsystems.

8.2 CONCLUSIONS AND RECOMMENDATIONS

1. Mainline monitoring stations need to be about 800 m (\approx 2,500 feet) apart.
2. Wrong-way detectors should be in the entry roadway of the HOV interchange so that errant vehicles can be detected before entry. Dynamic signing and warning systems should be used in conjunction with the detection subsystem. The HOV main line monitoring sites should monitor the progress of the wrong-way vehicle along the system.
3. When using induction loop detector pairs, use multi-conductor cable to construct them.
4. Use identical detector units and detector settings when induction loop detectors are the basic speed measurement system.

9.0 SPEED MEASUREMENT WITH INDUCTANCE LOOP SPEED TRAPS

9.1 SUMMARY

This phase of the research includes the use of inductance loop detectors in a freeway management situation to determine the optimal speed trap distance, best wire type, shortest and most consistent delay time configuration, and the most accurate speed detection hardware combination.

Using five different speed trap distances from 6 to 24 meters (20 to 80 feet) with a variety of detector units, controlled field tests were conducted. These test results form the basis for the following recommendations. It is not possible to identify a global optimal speed trap distance. The testing suggests that accurate speed measurements should not utilize different makes or models of detector units. For speed measurements to be accurate, the change in inductance necessary for a detection must be very similar between detector units. Identical make and model of detector units easily meet this criterion. The speed error for traps with identical detector units is about 2.4 km/h (1.5 mph) for all speeds. Errors for speed traps with different detector units were widely variable from 1.6 to 194 km/h (1 to 120 mph). The best method for obtaining accurate speeds with inductance loop detectors involves use of identical make and model detector units.

Executing a test program including single-conductor stranded wire and multi-conductor cable inductance loops allowed determination of the best wire type for accurate speed measurement. Measurements of speed using both wire types were compared to measurements using an infrared sensor trap. The multi-conductor cable inductance loop speed trap results in a speed difference from the infrared light sensor speed trap of only 0.224 km/h (0.139 mph). On the other hand, the single-conductor stranded wire speed trap measured a speed difference of about 10 km/h (6 mph). The best method for obtaining accurate speeds with inductance loops is to use multi-conductor cable.

The response time is the measured time from the arrival of a vehicle at an inductance loop edge to the actual detection of the vehicle. As the response time varies, so does the accuracy of speed measurement. Vehicle size, vehicle speed, detector type, detector sensitivity, and inductance loop wire type all affect the response time. The shortest response times occurred when the Naztec Card Rack detectors were used. The multi-conductor cable loops also had shorter delay times than did the single-conductor stranded wire loops.

Measuring vehicle speeds accurately with inductance loop detector speed traps depends upon the vehicle mix, vehicle speeds, detector type, and the detector sensitivity settings. While using a 9 meter (30 foot) trap, the speed difference between an inductance loop speed trap and an infrared light sensor speed trap is very small for most cases. As speeds increase, the speed difference also increases. Finally, the Naztec Card Rack detectors consistently measure the lowest speed differences for most conditions.

9.2 CONCLUSIONS AND RECOMMENDATIONS

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

9.2.1 Recommendations for Optimal Spacing of Speed Traps

1. To effectively use inductance loop detectors in measuring speed, use identical detector units to reduce the measurement error. Identical detector units reduce the average error at 129 km/h (80 mph) from a range of 16 to 194 km/h (10 to 120 mph) down to a range of 2.4 to 7.3 km/h (1.5 to 4.5 mph). This is a substantial reduction in the error of speed measurement. It demonstrates that the use of identical detectors operating on the same frequency and sensitivity level is preferable for measuring speeds.
2. Use the smallest trap distance practicable to help reduce the effects of lane-changing vehicles on the speed measurement process. The 9, 18, and 24 meter (30, 60, and 80 foot) trap distances gave the lowest average error, but no consistent pattern emerged to identify the optimal trap length. Because the 9 meter (30 foot) speed trap provides the least opportunity for vehicles to change lanes within the trap, it is the best compromise.

9.2.2 Recommended Inductance Loop Wire Type

To obtain the most accurate speed measurements with inductance loop speed traps, several features are necessary. These include construction of the inductance loops identically, and use of identical detectors, as shown above. The type of wire used in the construction of the inductance loop speed trap also affects the accuracy of speed measurement. Multi-conductor cable inductance loop speed traps provide significantly more consistent speed measurements when compared to speed measurements from the infrared trap. The multi-conductor cable loops yielded the lower speed differences and standard deviation of speed differences.

9.2.3 Recommendations Based on the Response Time Study

The response time is a complex interaction of many factors, including the vehicle size, vehicle speed, detector type, detector sensitivity, and inductance loop wire type. Agencies implementing inductance loop speed traps should know their vehicle mix and anticipate the vehicle speeds. The response time varies depending on these variables, thereby affecting the accuracy of the speed measurement. Various detectors and detector sensitivity settings will cause the response time to increase or decrease depending on the size and shape of the magnetic field created. Use

the same detector type and sensitivity setting to minimize error. Finally, multi-conductor cable inductance loop speed traps have shorter and more consistent response times than single-conductor stranded wire inductance loop speed traps.

9.2.4 Recommendations Based on the Speed Measurement Accuracy Study

The card rack detector system is best for measuring speed. In this study, the stand-alone detectors did not perform as well. Inductance loop detector speed traps in the freeway environment must accurately measure speeds of all vehicle types. For this reason, a card rack type detector for inductance loop speed traps should be used. Regardless of the detector type, frequent calibration of the detectors is necessary. At low speeds, the detector should measure vehicle speed accurately within 0.81 km/h (0.50 mph) and 1.61 km/h (1.0 mph). For higher speeds the calibration level should measure speed to about 4.83 km/h (3.00 mph). With this periodic calibration, accurate measurement of most vehicle speeds is possible.



10.0 OVERALL APPRAISAL

Because of the many uncontrollable variables that affect its performance and limit the accuracy and reliability of the inductance loop detector, it can never be a totally reliable method of data collection. At its very best, induction loop technology must be classified as a "wholesale" or macro-type technology for vehicle detection, where occasional failure in detection is tolerable. Typically, loop detectors have flourished in traffic signal applications where there are usually many opportunities to detect vehicle arrivals to "get the green". Because of its low cost and relative simplicity, the loop detector has survived and probably will continue to survive in such an environment.

As we move into the future of transportation management technology, there may be new demands on data collection systems that may not be met by the loop technology. The concept of an Intelligent Transportation System envisions a far more precise level of information availability than can generally be provided by loop detectors. Agencies are encouraged to examine newer technologies in the hope of finding a detection system that will meet the needs of the emerging information age.

