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Transportation Research Studies

ALTERNATIVE DRIVER INFORMATION TO ALLEVIATE WORK-ZONE-RELATED DELAYS

Final Report

Patrick T. McCoy
Geza Pesti
Patrick S. Byrd

Department of Civil Engineering
College of Engineering and Technology

W348 Nebraska Hall
Lincoln, Nebraska 68588-0531
Telephone (402) 472-2371
FAX (402) 472-8934

Sponsored by the
Nebraska Department of Roads
1500 Nebraska Highway 2
Lincoln, Nebraska 68509-4567
Telephone (402) 479-4337
FAX (402) 479-3975

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16. Abstract

The overall objective of the research documented in this report was to find better ways to control traffic at work zones on rural interstate highways. The primary focus was on improving the safety and efficiency of the merging operations in advance of lane closures. The research involved the identification and evaluation of alternative strategies designed to control traffic speeds and merging operations in advance of lane closures.

Twelve alternatives were identified as a result of a literature review, brainstorming session, and survey of states. The alternatives and the existing merge control strategy used by the Nebraska Department of Roads, NDOR Merge, were evaluated using computer simulation. In addition, field evaluations of the NDOR Merge and two alternatives, the Indiana Lane Merge and Late Merge, were also conducted. Field studies of the Indiana Lane Merge and the Late Merge were conducted at work zones in Indiana and Pennsylvania, respectively. Field studies of the NDOR Merge were conducted at work zones on I-80 in Nebraska. The field data were used to determine the safety and operational effects of these merge control strategies.

A benefit-cost analysis was performed to evaluate the cost-effectiveness of four alternative traffic control strategies relative to the NDOR Merge. The four alternatives evaluated were: (1) the Indiana Lane Merge, (2) Late Merge, (3) Enhanced Late Merge, and (4) "Smart" Work Zone. The Enhanced Late Merge is a traffic-responsive Late Merge. During low to moderate traffic volumes, early merging operations like the NDOR Merge are in effect. When traffic volumes are above a predetermined threshold, the Late Merge is in effect. The "Smart" Work Zone is capable of detecting congestion and providing real-time advisory information to travelers encouraging them to divert to an alternate route. The net benefits of the alternatives were calculated, and a breakeven analysis was performed to identify the most cost-effective alternatives over the range of traffic volumes and truck percentages expected on rural interstate highways in Nebraska over the next 20 years. The NDOR Merge was found to be the most cost-effective merge control strategy for directional ADTs below 16,000 to 20,500 vpd depending on the percentage of trucks. The Late Merge, Enhanced Late Merge, and "Smart" Work Zone were the most cost-effective alternative at higher traffic volumes. The Indiana Lane Merge was not found to be the most cost-effective alternative under any of the traffic conditions investigated.

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The project monitors were Dan Waddle, Traffic Engineering Division, and Dalyce Ronnau, Maintenance Division, NDOR. They coordinated the involvement of the NDOR in the research and provided project oversight and guidance to the research team. Their excellent cooperation contributed greatly to the successful completion of the research.

The efforts of Victor P. DeFazio, Assistant District Traffic Engineering, Engineering District 11-0, Pennsylvania Department of Transportation, and John "Wes" Shaw, Division of Construction, Crawfordville District, Indiana Department of Transportation, are gratefully acknowledged. Mr. DeFazio assisted the research team with local arrangements for the Late Merge field study, and Mr. Shaw assisted the research team with local arrangements for the Indiana Lane Merge field study.

DISCLAIMER

The contents of this report reflect the views of the authors who are responsible for the facts and accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of neither the Nebraska Departments of Roads, the Federal Highway Administration, nor the University of Nebraska-Lincoln. This report does not constitute a standard, specification, or regulation. Trade or manufactures' names, which may appear in this report, are cited only because they are considered essential to the objectives of the report. The U.S. government and the State of Nebraska do not endorse products or manufactures.

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Chapter 1

INTRODUCTION

BACKGROUND

This is the final report of Nebraska Department of Roads (NDOR) Research Project Number SPR-PL-1(35)P513, *Alternative Driver Information to Alleviate Work Zone-Related Delays*. The overall objective of the research was to find better ways to control traffic at work zones on rural interstate highways. The primary focus was on improving the safety and efficiency of the merging operations in advance of lane closures. The research involved the identification and evaluation of alternative strategies designed to control traffic speeds and merging operations in advance of lane closures.

Three methods were used to identify the alternatives: (1) literature review, (2) brainstorming session, and (3) survey of states. The participants in the brainstorming session included representatives of law enforcement, motor carriers, traffic control contractors, highway project engineers, highway maintenance engineers, traffic engineers, and the Federal Highway Administration. A total of 12 alternatives were identified.

The evaluation was conducted in three phases. The first phase involved preliminary field studies to determine the safety and operational effects of the existing traffic control plan used by NDOR. The results of the preliminary field studies provided the data for the calibration of the traffic flow models used to evaluate the alternatives in the second phase of the evaluation and the baseline performance measures for the evaluation of the alternatives in the third phase. In the second phase, a computer simulation study was performed to assess the operational effects of the 12 alternatives and the existing NDOR traffic control plan. Based on the results of the simulation study, NDOR selected two of the alternatives for evaluation in the field. The third phase of the evaluation involved the field study of the selected alternatives and a comparison of their safety and operational effects with those of the existing NDOR traffic control plan, which were found in the first phase. In addition, a benefit-cost analysis of the alternatives was conducted to identify the most cost-effective alternatives over the range of traffic volumes and truck percentages expected on rural interstate highways in Nebraska over the next 20 years.

CONTENTS OF REPORT

The procedures, findings, conclusions, and recommendations of the research are documented in this report. The preliminary filed studies of the existing traffic control plan, used by NDOR for lane closures on rural interstate highways, are described in Chapter 2. Results of the literature review, brainstorming session, and survey of states are presented in Chapter 3. The computer simulation study and the field studies of the selected alternatives are presented in Chapters 4 and 5, respectively. The benefit-cost analysis is reported in Chapter 6, and the conclusions and recommendations of the research are presented in Chapter 7.

Chapter 2

PRELIMINARY FIELD STUDIES

The traffic control plan typically used at work zones on interstate highways in Nebraska, NDOR Merge, was evaluated first to provide a frame of reference for the evaluation of alternative work zone control strategies. Therefore, field studies were conducted at work zones at two locations on I-80 in Nebraska. The preliminary field studies were conducted to:

1. determine the traffic flow characteristics and safety effects of the NDOR Merge, and

2. provide data for the calibration of the traffic flow models subsequently used in evaluating alternative work zone control strategies.

STUDY SITES

Only temporary work zones were available for the preliminary studies, because the schedule for the research did not enable the field studies to begin before the completion of the major road work on I-80 in the summer of 1997. Based on the site evaluation performed in the preliminary study design *(1)*, a work zone with a right-lane closure in advance of the Gretna exit on westbound I-80 was selected as the site for the preliminary field studies. However, since high levels of congestion were not observed during the studies at this site, preliminary field studies were also conducted at another site, in an effort to observe congested flow conditions. This second study site was a work zone with a right-lane closure in advance of the 13th Street exit on westbound I-80 in Omaha.

Gretna

The Gretna study site was a temporary work zone with a right-lane closure in advance of the Gretna exit on westbound I-80. It was located on a rural four-lane section of I-80, which had a 1996 ADT of approximately 30,000 vpd. The normal speed limit on the section was 75 mph. The sequence of traffic control devices in advance of the work zone was as follows:

- ROAD WORK 2 MILES sign
- RIGHT LANE CLOSED ½ MILE sign
- REDUCED SPEED AHEAD sign
- RIGHT LANE CLOSED 1500 FT sign
- Symbolic Right Lane Reduction Transition Sign
- SPEED LIMIT 65 sign with FINES DOUBLED plate
- REDUCED SPEED AHEAD sign
- SPEED LIMIT 55 sign with FINES DOUBLED plate
- Arrow Display Board

Except for the ROAD WORK 2 MILES sign, the locations of these signs, on both days when the preliminary studies were conducted, are shown in Figures 2-1 and 2-2. The signs were not in exactly the same locations on both days, because the work zone was a temporary zone which was set up at the beginning of each day. All of the signs, except the arrow display board, were located on both sides of the roadway.

The work zone could not be seen by approaching traffic at the ROAD WORK 2 MILES sign, because it was hidden from view by a crest vertical curve between the sign and the work zone. The work zone was hidden from the view of approaching traffic until the top of the crest, which was between the overpass and the RIGHT LANE CLOSED ½ MILE sign. The work zone approach between the RIGHT LANE CLOSED ½ MILE sign and the lane closure was on a sag vertical curve on a tangent section of I-80.

Omaha

The Omaha study site was a temporary work zone with a right-lane closure in advance of the 13th Street exit on westbound I-80 in Omaha. It was located on a urban four-lane section of I-80, which had a 1996 ADT of about 50,000 vpd. Although this site was not on a rural section of the interstate, it was selected in an effort to observe congested traffic flow conditions in a work zone merge area. The normal speed limit on the section was 60 mph. The sequence of traffic control devices in advance of the work zone was as follows:

- RIGHT LANE CLOSED AHEAD sign
- SPEED LIMIT 60 sign with FINES DOUBLED plate
- RIGHT LANE CLOSED ½ MILE sign
- RIGHT LANE CLOSED 1500 FT sign
- Right Lane Reduction Transition Sign
- SPEED LIMIT 50 sign with FINES DOUBLED plate
- Arrow Display Board

The locations of these signs, on the day that the preliminary study was conducted at this site, are shown in Figure 2-3. The signs at this site were located on only one side of the roadway.

The work zone could be seen by approaching traffic in advance of the RIGHT LANE CLOSED AHEAD sign. The work zone approach between the RIGHT LANE CLOSED AHEAD sign and the lane closure was on a slight upgrade on a tangent section of I-80.

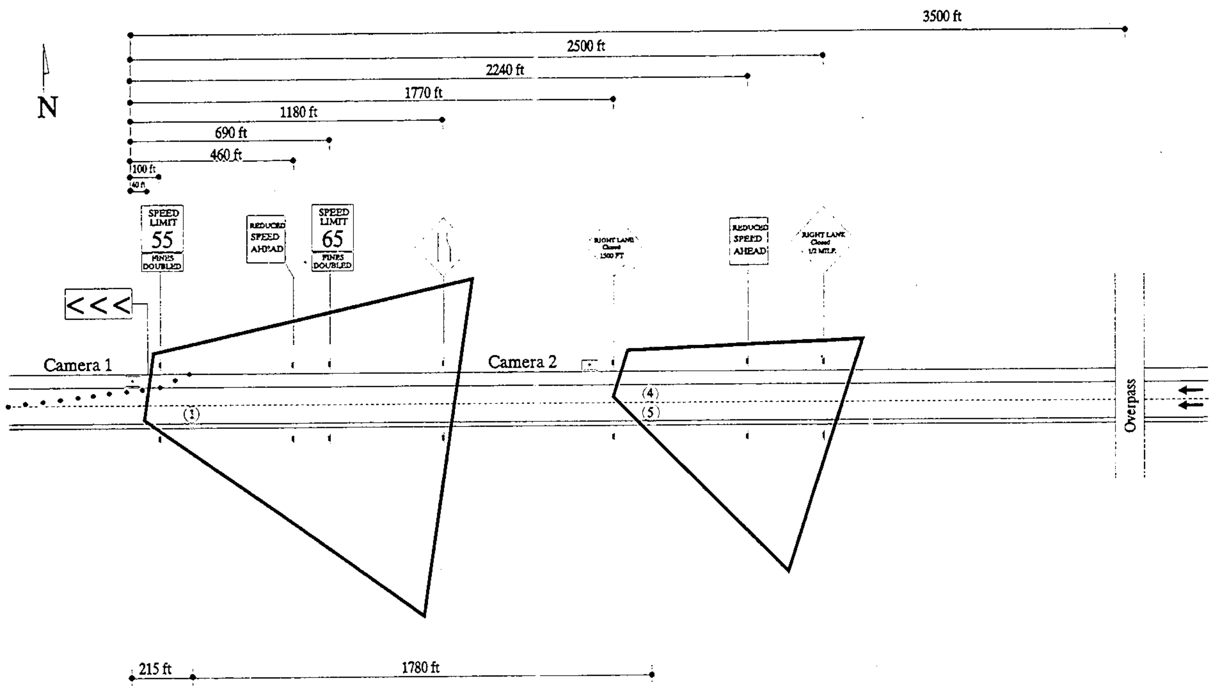


FIGURE 2-1 Gretna Study Site on September 20, 1997.

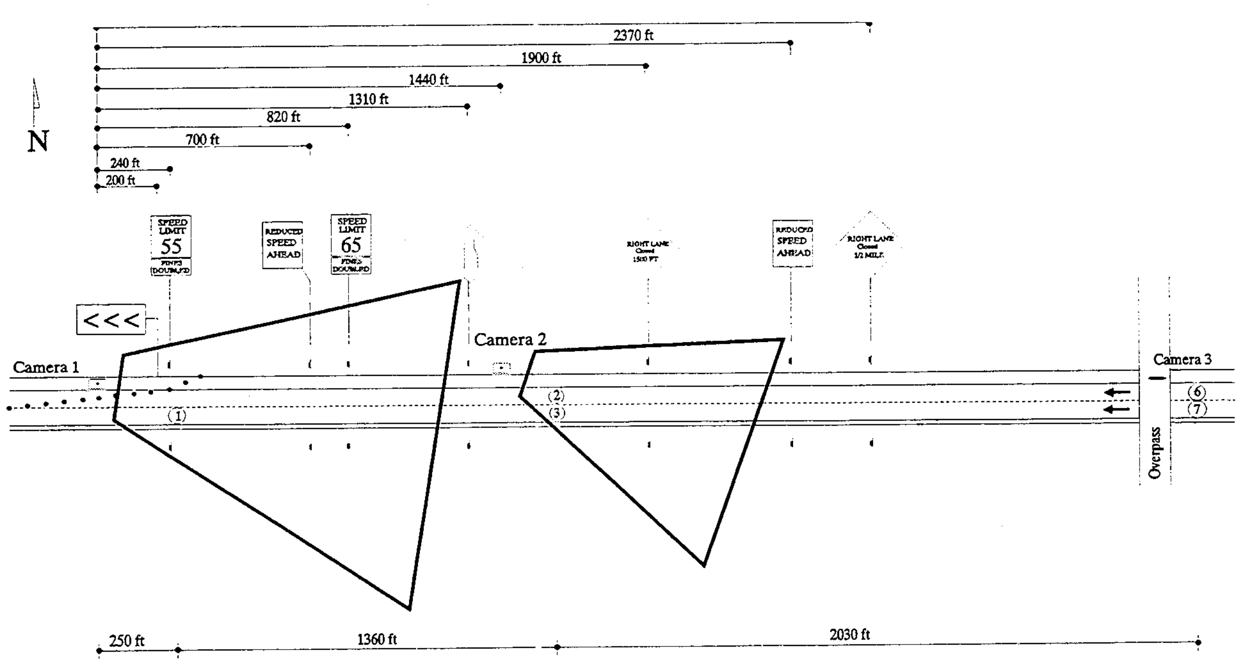


FIGURE 2-2 Gretna Study Site on October 1, 1997.

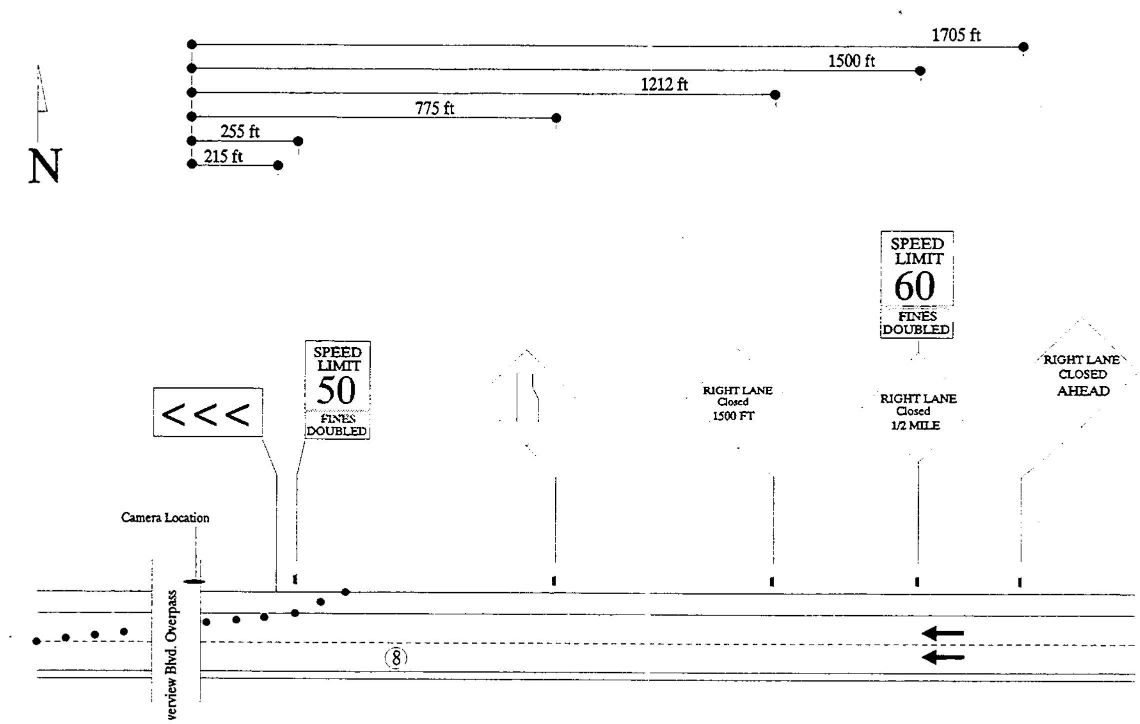


FIGURE 2-3 Omaha Study Site.

DATA COLLECTION

Video Data Acquisition System

Traffic data were collected at the study sites using the University of Nebraska-Lincoln's Video Data Acquisition System (VDAS). The VDAS consists of two mobile video recording platforms and an Autoscope video image analysis system. Each recording platform is housed in a 4-by-6 foot, two-wheel trailer, and includes: (1) a high-resolution video camera mounted on a 30-foot, pneumatic telescoping mast; (2) a high-grade video recorder/player; (3) a time-date character generator; (4) a video monitor; (5) remote pan/tilt camera controller; and (6) an AC power generator. Each platform is capable of monitoring traffic events occurring along several hundred feet of roadway. Event times are recorded to a precision of +/-0.017 second and can be extracted automatically using the Autoscope video image analysis system. The main components of the recording platforms are shown in Figure 2-4.

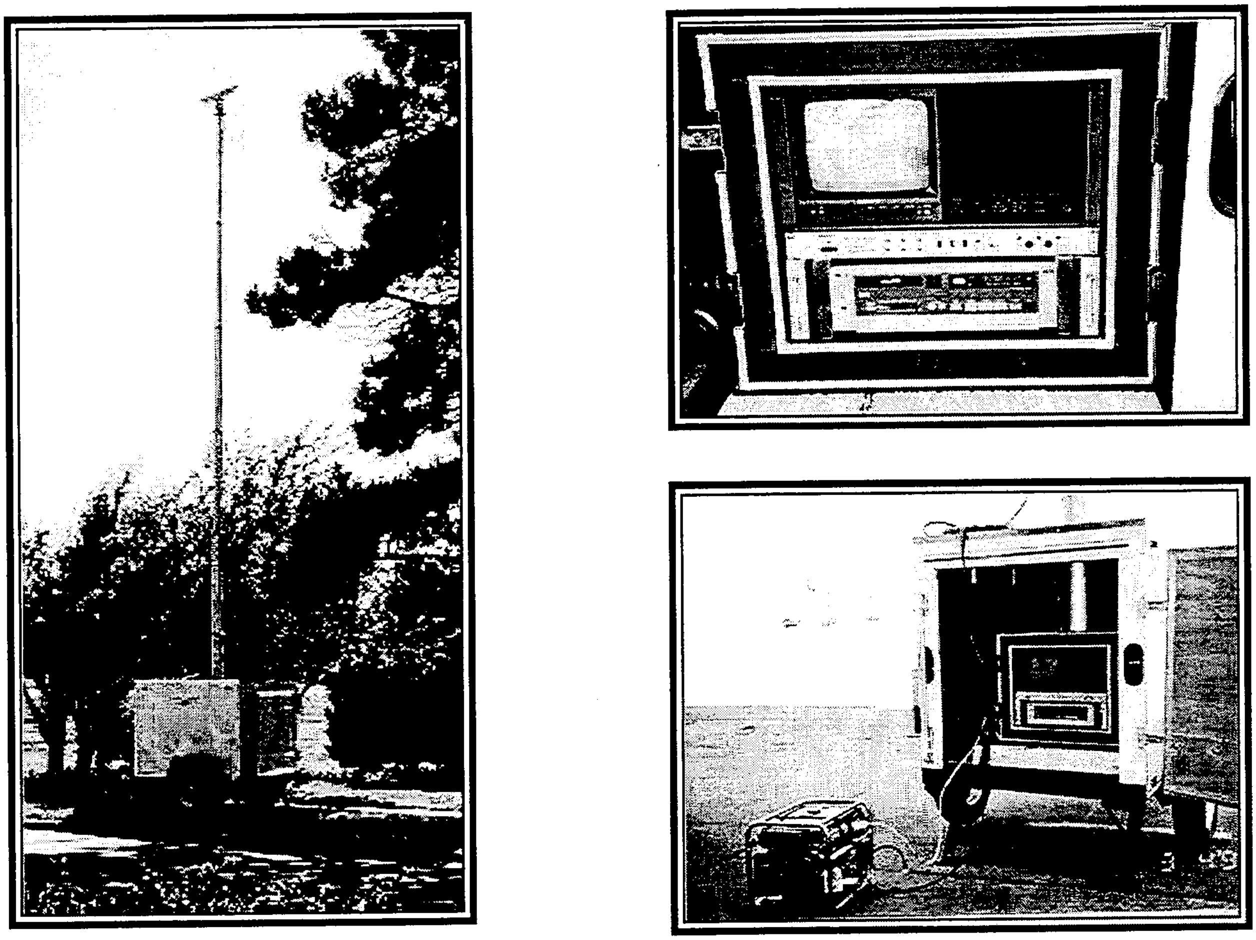


FIGURE 2-4 Main Components of the Video Recording Platform.

Gretna Study Site

Preliminary field studies were conducted at the Gretna study site on two days. Saturday, September 20, 1997, was the first day on which data were collected at this site. One of the VDAS recording platforms was located on the right shoulder about 100 feet downstream from the beginning of the lane closure taper as shown in Figure 2-5. The second platform was located off the right shoulder about 1,800 feet upstream from the beginning of the lane closure taper. These camera locations are shown in Figure 2-1. Traffic operations were video taped continuously at both locations for the 6-hour period from 10:30 am to 4:30 pm.

The second day on which data were collected at the Gretna study site was Wednesday, October 1, 1997. One of the VDAS recording platforms was located on the right shoulder about 240 feet downstream from the beginning of the lane closure taper. The second platform was located off the right shoulder about 1,400 feet upstream from the beginning of the lane closure taper. The location of the second camera was moved about 400 feet closer to the beginning of the lane closure taper than it was on the first day in order to obtain better coverage of the area where the majority of

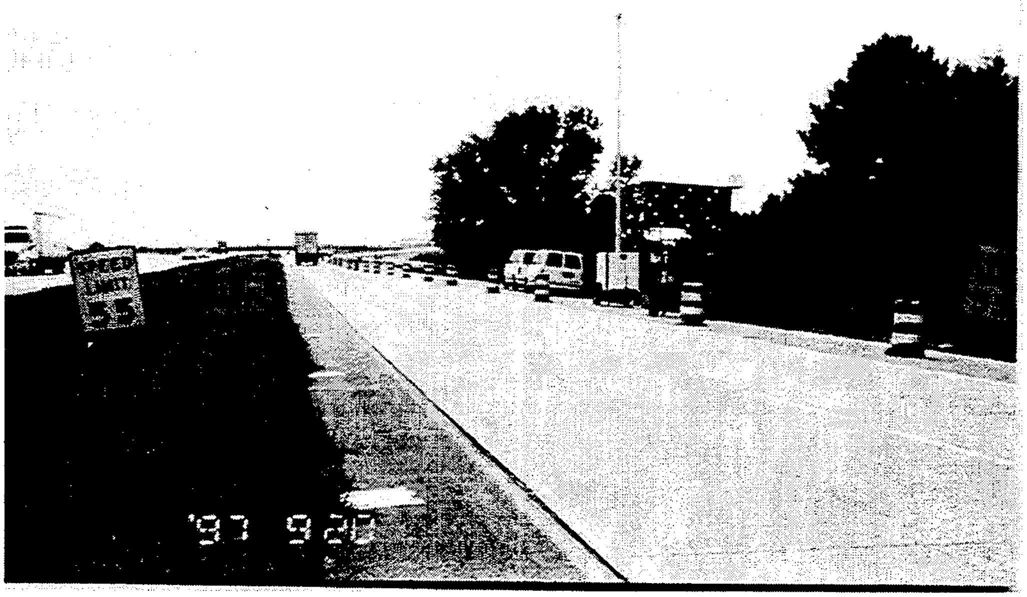


FIGURE 2-5 Camera Location Behind the Taper at the Gretna Study Site.

the merging operations occurred. These camera locations are shown in Figure 2-2. Traffic operations were video taped at both locations for a 10-hour period between 7:30 am to 6:30 pm.

On the second day, a camcorder was used in addition to the two cameras on the VDAS recording platforms. It was mounted on a tripod and placed on the overpass approximately 1,000 feet in advance of the RIGHT LANE CLOSED ½ MILE sign as shown in Figure 2-2. It was used to record approaching traffic in advance of the overpass. At this point, the approaching traffic could not see the work zone and had not been informed that there was a lane closure. Therefore, the traffic flow at this location was assumed to be representative of normal conditions. Traffic operations were video taped periodically at this location for a 1½-hour period between 7:30 am to 6:30 pm.

Omaha Study Site

A preliminary field study was conducted at the Omaha site on Tuesday, November 4, 1997. The purpose of this study was to observe congested flow in the merge area in advance of a lane closure, because congested flow had not been observed at the Gretna study site. Suitable locations at which to position the VDAS recording platforms were not readily available at this study site. Therefore, video taping was done from the Riverview Boulevard overpass as shown in Figure 2-6.

During the time of the study, the temporary work zone was usually setup about 9:00 am and removed by 4:00 pm. Consequently, it was not possible to record traffic during the morning and afternoon peak periods. However, based on the experience of the NDOR project manager, congested flow conditions were expected to occur during the noon hour. Therefore, traffic operations were video taped from 11:00 am to 3:00 pm at this location.

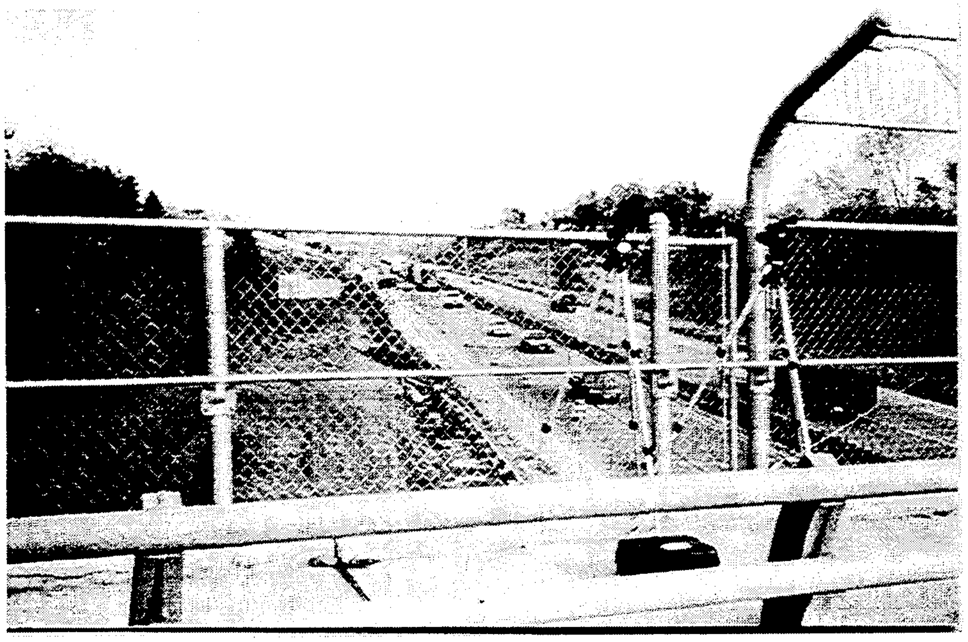


FIGURE 2-6 Video Recording at the Omaha Study Site.

ANALYSIS OF DATA

The video recordings taken at the preliminary field study sites were analyzed using the Autoscope video image analysis system. The data obtained from the Autoscope analysis were then analyzed to determine measures of effectiveness and the parameters needed for the calibration of the traffic flow model(s) used to evaluate alternative work zone control strategies. The video tapes were also reviewed manually to identify the traffic conflicts associated with merging operations which were used as measures of safety effectiveness in the evaluation of the alternative work zone control strategies field tested during the summer of 1998. The procedures and results of these analyses are reported in this chapter.

Autoscope Analysis

The Autoscope provides a means of automating traffic surveillance. Using a software-based video image analysis technology, the Autoscope is able to determine the following traffic parameters:

- vehicle presence and passage;
- vehicle speed and length; and
- flow rate, volume, lane occupancy, and headway over time.

The Autoscope analysis was conducted at selected points on the roadway within the field of view at each camera location. To derive traffic data from the video tapes, Autoscope detectors were placed in the video image at the desired locations of the data analysis points. An Autoscope detector, placed at the Data Analysis Point 1 at the Gretna study site, is shown in Figure 2-7. Data were

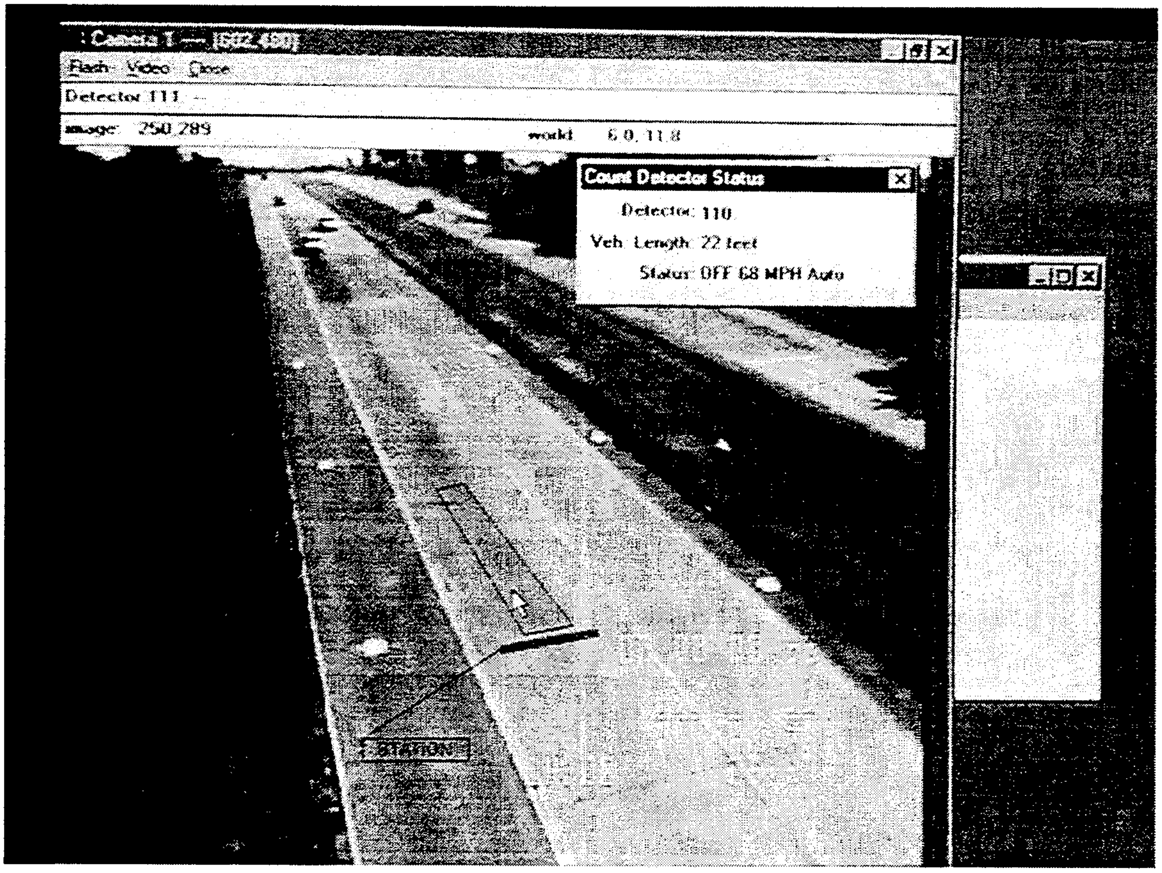


FIGURE 2-7 Autoscope Detector Observing Speed and Vehicle Length.

collected in this way at seven points at the Gretna study site, and at one point at the Omaha study site. The locations of data analysis points (Points 1 through 7) at the Gretna study site are shown in Figures 2-1 and 2-2. The location of the data analysis point (Point 8) at the Omaha study site is shown in Figure 2-3.

Lane Distribution

Previous research *(2,3,* and *4)* has found that the lane distribution of traffic approaching a lane closure is an indication of the effectiveness of the lane closure traffic control plan. Plans that cause traffic in the closed lane to move to the open lane sooner are usually associated with smoother traffic operations in the merge area. Therefore, lane distribution data were collected during the field studies. In addition, lane distribution was also used to calibrate the traffic flow models used in the simulation studies of the alternatives described in Chapter 4.

The lane distribution of the traffic approaching the lane closure at the Gretna study site is shown in Figure 2-8. At a distance of 4,000 feet in advance of the taper, 65 percent of the traffic was in the closed (right) lane and 35 percent of the traffic was in the open (left) lane. At this location, approaching traffic could not see the work zone and had only been informed that there was road work ahead, but not that there was a lane closure. The lane distribution was equal at a distance of 1,700 feet, which was about midway between the RIGHT LANE CLOSED 1500 FT signs and the

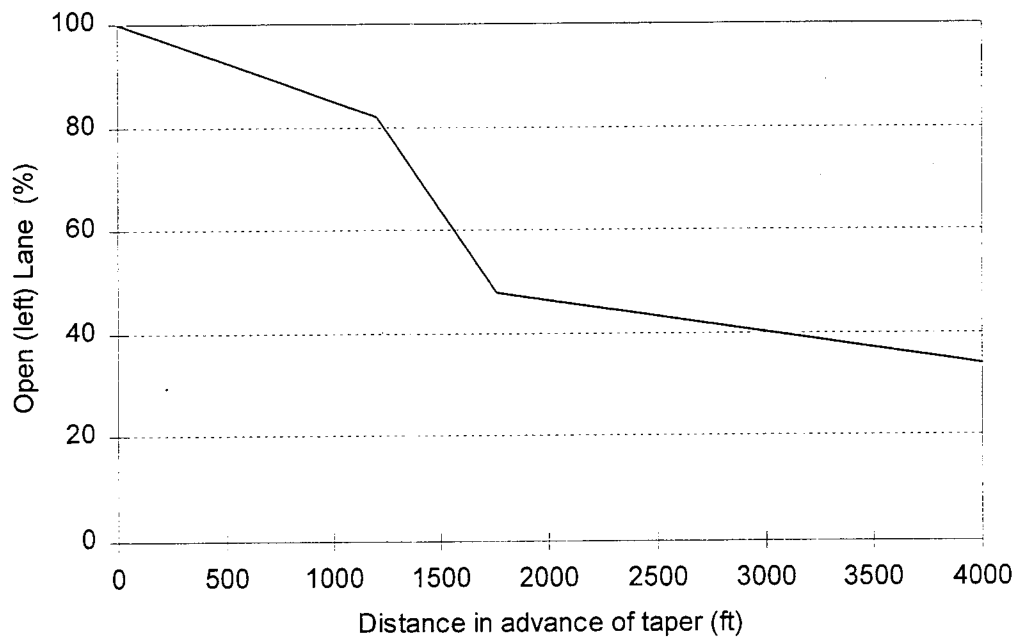


FIGURE 2-8 Lane Distribution at the Gretna Study Site.

symbolic right lane reduction transition signs. However, approximately 20 percent of the traffic was still in the closed lane at a distance of 1,200 feet in advance of the taper. In other words, about 50 percent of the traffic that was initially in the closed lane moved to the open lane somewhere between the RIGHT LANE CLOSED 1500 FT signs and the symbolic right lane reduction transition signs. Approximately an additional 30 percent moved to the open lane after passing the symbolic right lane reduction transition signs.

Speeds

The speed of traffic approaching the work zone traffic control area is a primary traffic flow model input variable. Also, the speeds of traffic at various points within the work zone traffic control area are indications of the safety and efficiency of merging operations in advance of the lane closure.

The speed data collected at each study site's data analysis points are shown in Table 2-1. At the Gretna study site, the speeds at Data Analysis Points 6 and 7 were representative of traffic flow under normal conditions, because the traffic at these points could not see the work zone and had not been informed that there was a lane closure ahead. As expected, the mean speeds in the open lane were higher than those in the closed lane. Also, the mean speeds were lower and the standard deviations were higher at the points closer to the lane closure, which is indicative of the increased merging occurring at these points.

The speed distributions observed at the lane drops at both study sites (*i.e.*, data analysis points 1 and 8) are shown in Figure 2-9. The Kolmogorov-Smirnov goodness of fit test, conducted at the 0.05 level of significance, found that the speeds at the data analysis points were normally distributed with the means and standard deviations shown in Table 2-1.

TABLE 2-1 Basic Speed Statistics.

Study Site	Data Analysis Point	Lane	Sample Size	Speed (mph)			
				Mean	Std. Dev.	Minimum	Maximum
Gretna	1	Open	15,661	57	7.6	40	84
	2	Closed	1,654	61	7.4	40	88
	3	Open	8,000	63	8.2	40	88
	4	Closed	1,525	62	7.5	40	83
	5	Open	2,751	65	7.7	40	83
	6	Closed	827	68	7.4	44	80
	7	Open	622	73	6.9	41	86
Omaha	8	Open	1,766	45	7.3	25	74

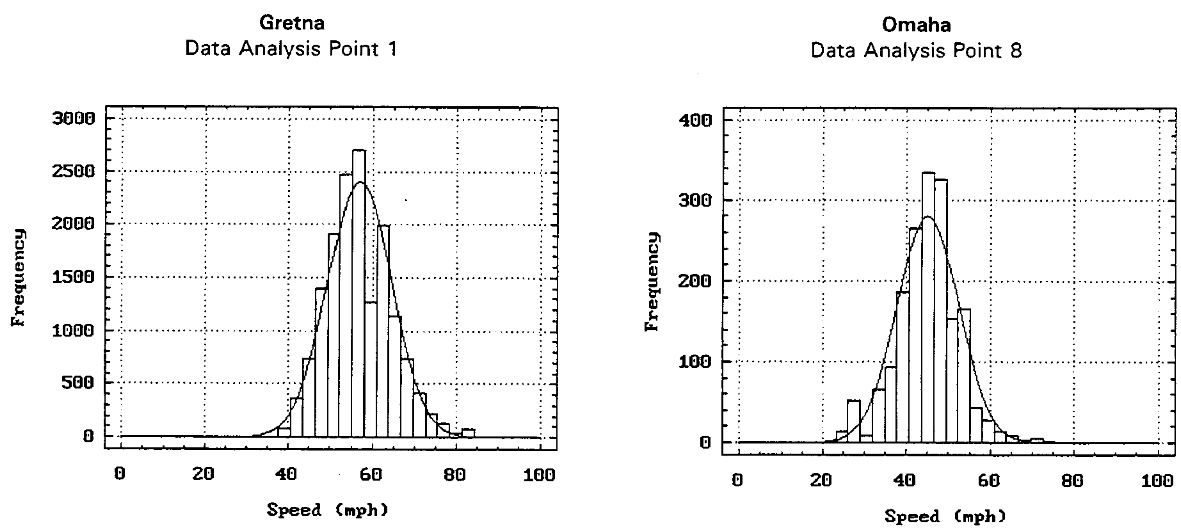


FIGURE 2-9 Speed Distributions.

Headways

Vehicle headway distribution is a parameter used to calibrate the traffic flow models used in the evaluation of the alternative work zone control strategies, which is described in Chapter 4. This distribution affects the ability of vehicles to merge from the closed lane to the open lane. A headway must be larger than the driver's acceptable gap size in order for a smooth merge to occur. Headway distributions with higher percentages of headways greater than the acceptable gaps of drivers will facilitate the merging operations.

The headway data collected at the data analysis points at the study sites are shown in Table 2-2. The mean headway is the inverse of the mean flow rate. Therefore, at the Gretna study site, the mean headways were smaller in the open lane at the data analysis points closer to the lane closure, because of the traffic merging from the closed lane to the open lane as it approached the lane closure. The Kolmogorov-Smirnov goodness of fit test conducted at the 0.05 level of significance found that the headway distribution at each data analysis point fits a shifted negative exponential distribution with the mean headway shown in Table 3-3 and a minimum headway of 0.4 seconds.

TABLE 2-2 Headway Data.

Study Site	Data Analysis Point	Lane	Sample Size	Headway (sec)			
				Mean	Std. Dev.	Minimum	Maximum
Gretna	1	Open	14,951	3.4	3.5	0.3	42
	2	Closed	1,462	7.6	7.5	0.3	53
	3	Open	7,593	4.2	4.9	0.2	55
	4	Closed	1,248	11.4	11.1	0.3	93
	5	Open	2,495	4.5	5.0	0.3	39
	6	Closed	697	5.3	4.4	0.3	37
	7	Open	569	7.4	9.4	0.3	64
Omaha	8	Open	1,637	2.6	2.7	0.3	24

Speed-Flow-Density Relationships

The fundamental speed-flow-density relationships of traffic flow are commonly used to assess the quality and capacity of traffic operations *(5)*. The speed-flow-density relationships observed during the preliminary field studies are shown in Figure 2-10. Each data point represents average speed, flow and density over a 15-minute period. The relationships are shown for the traffic flow at the taper. The data points corresponding to the Gretna study-site are marked by empty circles, and those points which were obtained from the data collected in Omaha are marked by filled circles. The cluster of data points at the highest density and flow were observed at the Omaha study site.

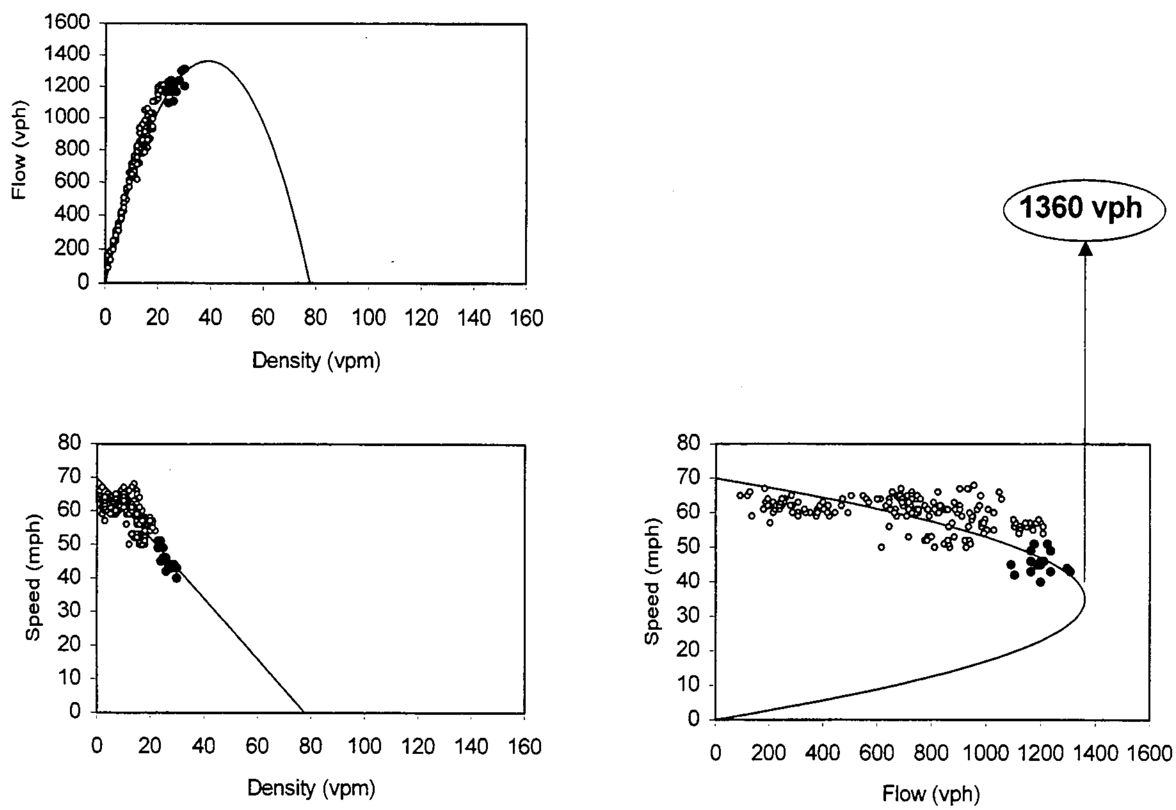


FIGURE 2-10 Speed-Flow-Density Relationships.

Although congested flow conditions were not observed at either study site, the composite plots of the data from the two sites indicate that the traffic flow at the Omaha study site may have been approaching the capacity of the single lane closure at the taper.

A linear speed-density relationship was fitted to the data points. The flow-density and speed-flow relationships derived from the fitted linear function suggest that the work zone capacity is approximately1,360 vph.

Traffic Conflicts

Traffic conflicts are used as a measure of accident potential. There are two basic types of traffic conflicts: (1) evasive actions (braking or weaving) by drivers to avoid collisions and (2) traffic violations *(6)*. Traffic conflicts were used as a measure of the safety effectiveness of the alternative work zone control strategies studied in the field.

The video tapes recorded during the preliminary field studies were reviewed to identify traffic conflicts associated with the merging operations in advance of the lane closures. Three types of conflicts were noted:

1. *Forced merge conflict*: a vehicle in the closed lane attempted to merge into the open lane, which caused either: (a) it to take evasive action to avoid colliding with vehicles in the open lane, or (b) vehicles in the open lane to take evasive action to avoid colliding with it.

2. *Lane straddle conflict*: a vehicle straddled the centerline of the roadway occupying both lanes in effort to prevent other vehicles from passing it in the merge area.

3. *Other conflicts*: other evasive actions or traffic violations that occurred in the merge area.

The numbers of traffic conflicts and the traffic volumes were noted for each hour of video tape recorded at both the Gretna and Omaha study sites.

Forced merges and lane straddles were the only types of conflicts observed during the preliminary field studies. About 70 percent of the conflicts observed were forced merges. Both of these conflicts were related to traffic density as shown in Figure 2-11. A simple linear regression analysis of these data found the following relationships between these conflicts and traffic density:

$$F = -7.72 + 0.844D \quad \textbf{(2-1)}$$

$$L = -2.53 + 0.210D \quad \textbf{(2-2)}$$

where,

	F	=	number of forced merges per hour;
	L	=	number of lane straddles per hour; and
	D	=	traffic density (vpm).

These relationships were statistically significant at the 0.05 level, and their R^2 values were 0.70 and 0.54, respectively.

Both forced merges and lane straddles increased with density according to Equations 2-1 and 2-2. Forced merges increased with density at about four times the rate at which lane straddles did. The relationships indicate that the forced merges and lane straddles do not occur at densities below approximately 10 vpm.

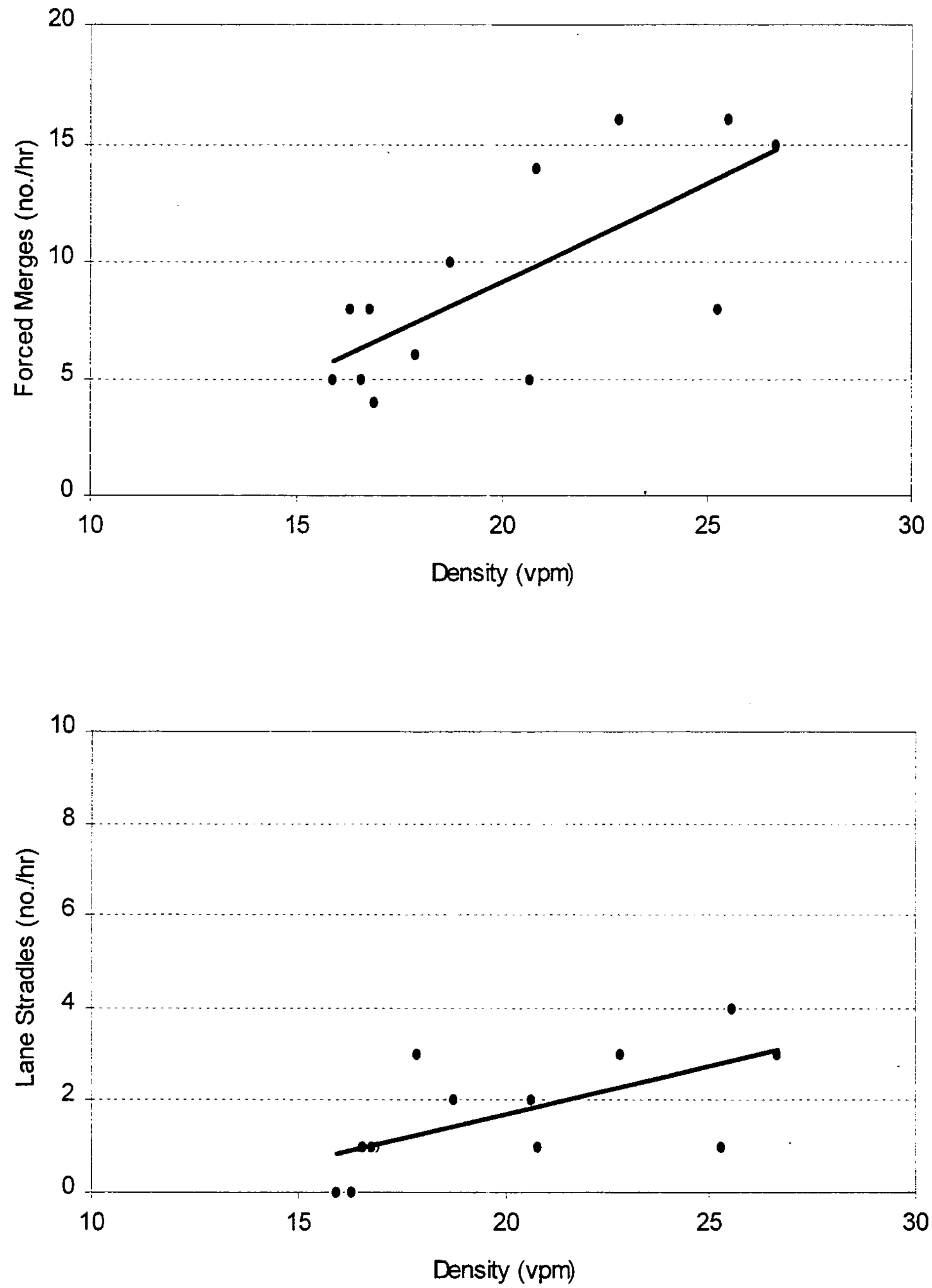


FIGURE 2-11 Traffic Conflicts.

SUMMARY

The preliminary field studies were conducted to develop a better understanding of traffic operations in advance of lane closures on rural interstate highways, and to obtain data for the calibration of the traffic flow models used in evaluating alternative work zone control strategies. In addition, the analysis of the data collected provided measures of the operational and safety effects of the existing work zone control strategy used by NDOR. These measure were used as the base line values to which the results of the field studies of the selected alternatives are compared in Chapter 5.

The objectives of the preliminary field studies were achieved. Sufficient speed, volume, density, headway, lane distribution, and traffic conflicts data were collected to calibrate the traffic flow models as well as establish the basis for comparing the operational and safety effects of the alternative work zone control strategies. The preliminary field studies revealed the importance of considering the effects of traffic volume on the measures of effectiveness to be used in the evaluation of the alternative work zone control strategies. Speed-flow-density relationships and traffic conflicts-density regression equations were found to account for the volume effects, and they were used in the evaluation of alternative work zone control strategies as described in Chapter 5.

In addition, the preliminary field studies demonstrated that VDAS provided all of the data necessary for the calibration of traffic flow models and the evaluation of alternative work zone control strategies. Proper study design and deployment of the VDAS recording platforms were found to eliminate the potential data analysis problems associated with the Autoscope video imaging processing system.

Chapter 3

ALTERNATIVE WORK ZONE CONTROL STRATEGIES

The objective of this research is to find better ways to control traffic through work zones on rural interstate highways. The primary focus is on ways to: (1) improve the safety and efficiency of merging operations in advance of lane closures and (2) reduce the speed of traffic in work zones. Three methods were used to identify alternative work zone control strategies for consideration. These methods included: (1) literature review; (2) brainstorming; and (3) survey of states. The procedures and results of these efforts to identify alternative work zone control strategies are presented in this chapter.

LITERATURE REVIEW

A literature review was conducted to provide a frame of reference for the research. The scope of the literature review was not limited to work zone control strategies. It included six subject areas related to work zones, which were: (1) work zone capacity; (2) work zone merge operation; (3) devices used to communicate with drivers approaching work zones; (4) potential for driver diversion; (5) control devices used to regulate traffic in advance of, at entry to, and within the work zone; and (6) devices used to monitor and control work zone traffic flow in real-time.

Findings of the literature review are presented in Appendix A. Six studies were found that pertained to work zone control strategies.

Iowa Weave

One of the earliest reported studies on work zone traffic control strategies was a safety evaluation of the Iowa Weave conducted by Brewer in 1972 *(7)*. The Iowa Weave is a lane-closure pattern that was developed by the Iowa State Highway Commission to slow traffic in advance of lane closures at work zones on interstate highways. As illustrated in Figure 3-1, the pattern first forces traffic to merge into the open lane, then the single lane of traffic is moved from the open lane to the closed lane and back again. The results of the study indicated that the Iowa Weave was effective in reducing speeds when there was activity in the work area. More than 50 percent of all vehicles sampled traveled below the posted 30-mph work zone speed limit; whereas less than 20 percent complied with this speed limit when the Iowa Weave was not in place. Also, no excessive confusion and very few hazardous or unusual maneuvers by drivers negotiating the Iowa Weave were observed. It was concluded that the Iowa Weave was a safe and effective traffic control method.

Since the study by Brewer was completed, the Iowa Department of Transportation has stopped using the Iowa Weave. As a result of the low design speed of its geometrics, an excessively high number of traffic control devices were struck by vehicles negotiating the weaving pattern. When the design of the pattern was modified to reduce the number of traffic control devices struck by traffic, the speed control effects of the pattern were lost. Therefore, the Iowa Department of Transportation no longer uses the Iowa Weave.

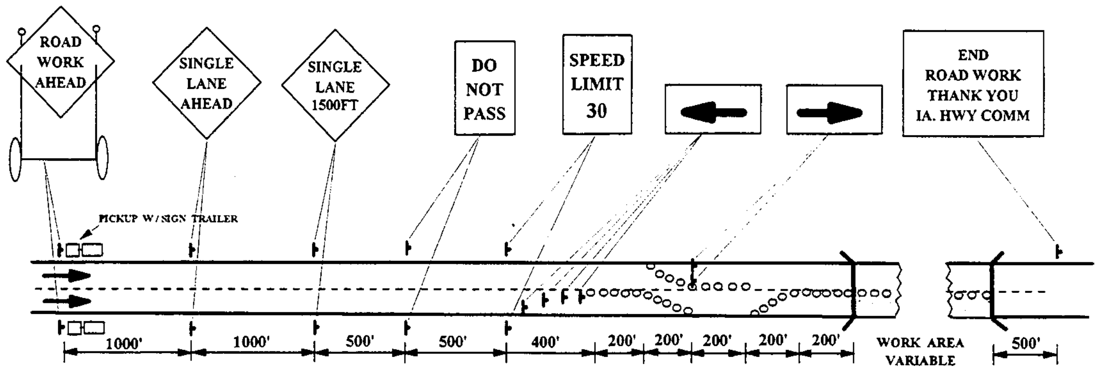


FIGURE 3-1 Iowa Weave.

Changeable Message Signs

The effectiveness of changeable message signs (CMSs) in advance of freeway lane closures was evaluated by Hanscom in 1982 *(2)*. Traffic operations studies and driver surveys were conducted in four states to determine the optimum CMS locations and messages. A distance of 0.75 miles in advance of the lane closures was found to be the preferred CMS location in terms of increased preparatory lane-change activity, smoother lane-change profiles, significantly fewer late lane changes, and reduced speeds at the lane-closure point. The results of the driver surveys indicated that drivers favored messages containing both speed and lane closure advisories.

Based on these findings, the following guidelines for the use of CMSs were recommended:

1) Message presentation format should permit the maximum amount of information to be displayed at a glance (*i.e.*, 3-lines display with a maximum of two phases).

1) CMSs should be located 0.75 miles in advance of lane closures.

2) CMSs should supplement, not replace, conventional traffic control devices used in advance of lane closures.

3) CMSs should not be used in place of arrow boards, which have much greater impact on the safety of traffic operations in advance of lane closures on freeways.

Simulation Studies of Freeway Work Zone Lane Closures

Two simulation studies of freeway work zone lane closures have been published. The first study *(3)*, reported in 1982, developed and validated a microscopic simulation model to investigate the effects of advance warning and speed control on the efficiency of traffic operations. Control strategies designed to encourage drivers to merge into the open lane earlier were found to significantly reduce the frequency of forced merges, especially at higher traffic volumes. The implementation of a 45-mph speed limit in advance of the lane closure not only increased delay but also increased the frequency of forced merges in the taper area. The study concluded that: (1) early merging should be encouraged when traffic volumes exceed 1,000 vph, and (2) a lower speed limit may not be desirable from the standpoint of smooth merging operations.

The second simulation study *(4)*, reported in 1990, was conducted to determine an optimum merging strategy for traffic in advance of a freeway lane closure. It was found that the merging strategy had a significant impact on the average travel time through the work zone, especially at flow rates between 1,500 and 2,000 vphpl. As traffic volumes increased, the optimum merge strategy suggested that the first attempts by traffic in the closed lane to merge into the open lane should be made further downstream (*i.e.*, closer to the work zone), in order to minimize travel time through the work zone.

Speed Monitoring Displays

The effectiveness of a speed monitoring display in reducing speeds in work zones on interstate highways was evaluated by McCoy *et al (8)* in 1992. The device, developed by the South Dakota Department of Transportation, measures and displays the speeds of vehicles approaching the work zone; thereby, making drivers aware of how fast they are traveling and presumably causing them to reduce their speeds. The speeds are measured by radar and presented to the drivers on a digital display panel as shown in Figure 3-2. The results of before-and-after field studies indicated that the speed monitoring display did reduce the mean speed of traffic by about 5 mph and the frequency of drivers exceeding the advisory 45-mph speed limit by as much as 40 percent. However, it was noted that the sign assembly contained too much information for some drivers to comprehend, which may have limited the display's effectiveness.

Also in 1992, Garber and Patel *(9)* evaluated the effectiveness of a radar-equipped CMS in reducing speeds at work zones in Virginia. The CMS is designed to warn drivers that they are traveling above the maximum safe speed. When approaching vehicles are detecting traveling above a predetermined speed threshold, the CMS displays a message advising drivers that they are speeding and warning them to slow down as shown in Figure 3-3. The results of the study indicated that the radar-equipped CMS significantly reduced the speeds of speeding drivers.

In 1998, Garber and Srinivasan *(10)* reported on a follow-up study of the radar-equipped CMS to determine its long-term effectiveness in reducing speeds in work zones. The results of the study indicated that the CMS remains an effective speed control device for prolonged periods of deployment. Therefore, it was concluded that the radar equipped CMS is a very effective device for controlling speeds in both short-term and long-term work zones.

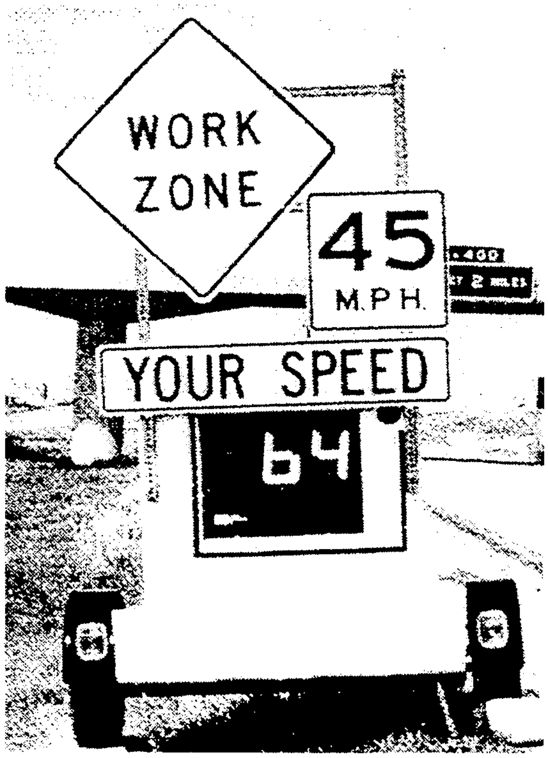


FIGURE 3-2 South Dakota Speed Monitoring Display.

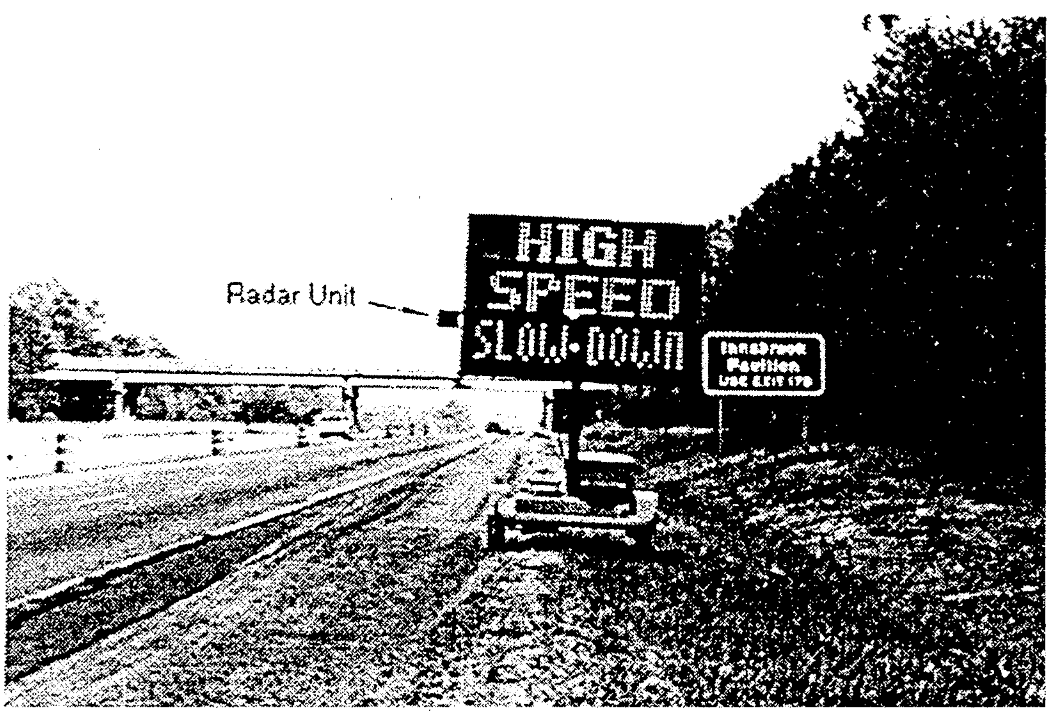


FIGURE 3-3 Radar-Equipped Changeable Message Sign.

BRAINSTORMING SESSION

In an effort to generate some new ideas from different perspectives for consideration in the research, a brainstorming session was held at the NDOR on December 18, 1997. Participating in the session were representatives of law enforcement, motor carriers, traffic control contractors, highway project engineers, highway maintenance engineers, traffic engineers, and the Federal Highway Administration. A list of the participants is included in the meeting notes in Appendix B.

Problems

The session began with a statement of the problem being addressed and a description of the NDOR Merge at lane closures on rural interstate highways, which is shown in Figure 3-4. The participants were then asked to describe their experiences and observations regarding the safety and efficiency of traffic operations at these locations.

Speeding, aggressive drivers, and lack of enforcement to discourage such behavior were listed as problems. However, it was also noted that the current plan does not provide sufficient space for effective law enforcement. Stopping violators is very difficult, especially during periods of high traffic volumes.

A number of problems associated with traffic congestion during high traffic volumes were cited by the participants. These included: (1) the high accident potential related to shock waves caused by traffic congestion and (2) the difficulty drivers have in knowing which lane is closed when the queues extend back beyond the lane closure signs in advance of the work zone. Also mentioned was the frustration experienced by drivers who merge early during periods of congestion and are passed by other drivers who remain in the closed lane and then merge into the open lane ahead of them. This behavior tends to infuriate the early mergers, who may then make it difficult for the late mergers to enter the open lane. Truck drivers often block the closed lane with their vehicles to prevent the late mergers from passing them.

The motor carrier representatives indicated that the trucks have difficulty negotiating the travel path provided by some work zone traffic control plans. The lanes are sometimes too narrow for travel at reasonable speeds, especially when there are strong cross winds. Also, the length of the merge area is often too short for trucks, especially if they must merge from the left lane to the right lane.

The credibility of work zone signing was also identified as a problem. Too often lanes seem to be closed for no apparent reason, or the length of the lane closure is much longer than necessary. Particularly irritating to drivers are lane closure advisory signs left in place when the lanes are no longer closed. On the other hand, the difficulty and danger associated with the placement of work zone traffic control devices is a concern of the contractors. Shorter lane closures and frequent traffic control device set-ups and take-downs increase the safety risk to the contractors.

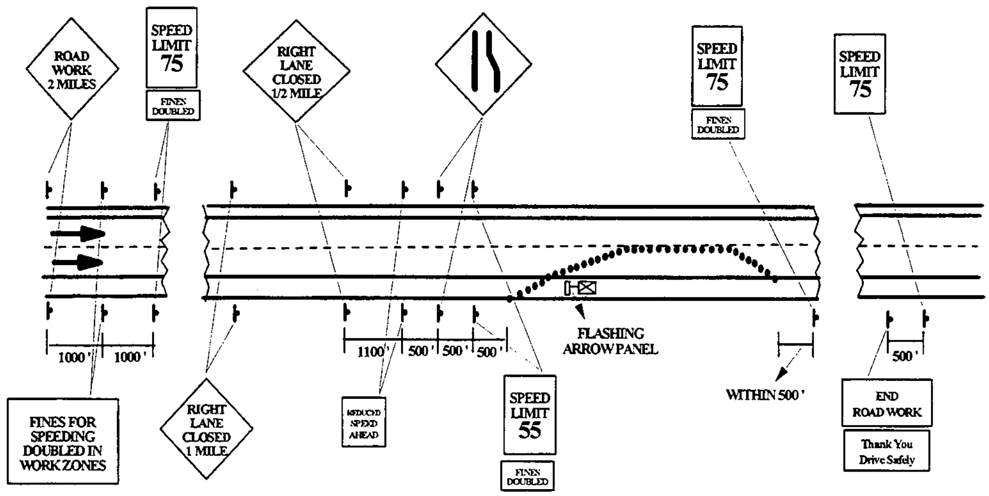


FIGURE 3-4 Merge Control Strategy Used by the Nebraska Department of Roads.

Possible Improvements

Following the discussion of problems related to work zone traffic control at lane closures on rural interstate highways, the participants were asked to suggest ways to solve the problems that had been identified. A total of 41 improvements were recommended. These suggestions represented a wide variety of ideas, which ranged from the addition of more traffic control devices to the provision of more law enforcement to the dissemination of more driver information about work zones. A list of the ideas generated is included in the meeting notes in Appendix A.

After all of the suggestions had been made, the participants identified the ideas that they considered to be the most promising. The participants selected 12 ideas as the best options that should be considered for further evaluation by the research team. A brief description of these possible improvements follows.

Longer Speed Zone Transition

In the traffic control plan for a typical lane closure, 75-mph speed limit signs with FINES DOUBLED supplementary plates are located about 8,560 feet in advance as shown in Figure 3-4. If there is a 55-mph work zone speed limit, it is designated by 55-mph speed limit signs with FINES DOUBLED supplementary plates installed approximately 500 feet in advance of the taper. The proposed improvement replaces the 75-mph speed limit signs with 65-mph speed limit signs when a 55-mph work zone speed limit is used. This would provide a longer and smoother speed transition between the 75-mph and the 55-mph speed zones, which is intended to encourage speed reductions by drivers in advance of the work zone and facilitate law enforcement by providing more room to stop speeders.

Maintain Credibility of Lane Closure Signing

Advance lane closure signs, that are not removed when the closed lanes are reopened, cause drivers to make unnecessary lane changes which not only annoys them but also causes them to lose respect for work zone traffic control devices. As a result, the effectiveness of work zone traffic control is diminished. Prompt removal of advance lane closed signs, when the closed lanes are reopened, is essential to achieving the objective of safe and efficient traffic operations in work zones.

Always Close Left Lane

The current practice is to close the lane in which the work area is located. If work is being done in the left lane, the left lane is closed; and if work is being done in the right lane, the right lane is closed. The proposed improvement would always close the left lane in advance of median crossovers and lane closures, even if the work is being done in the right lane. This would enable drivers to know that they must be in the right lane if there is a lane closure; and thus, drivers may be prepared to move to the open lane further in advance of the work zone. This may be especially helpful to truck drivers, because it would provide more time for them to perform the left-to-right merge, which is more difficult than the right-to-left merge, according to the participants of the brainstorming session.

Work Zone Information at Rest Areas and Fuel Stops

Real-time information about the locations, lanes closed, and traffic conditions in work zones provided at rest areas and fuel stops would enable drivers to know what to expect before they resumed their travel on the roadway. Some may choose to alter their travel plans in order to avoid congestion in the work zones, which would reduce the traffic demand and congestion in the work zones. Those who continue their trips would be better prepared to deal with conditions in the work zones by knowing which lanes are closed and where to expect travel delays.

Advance Changeable Message Signs

Real-time information about the locations, lanes closed, and traffic conditions in work zones provided on changeable message signs placed at interchanges in advance of the work zones would tell drivers what to expect ahead while traveling on the roadway. The information would enable them to exit at the next interchange and avoid congestion in the work zones. This in turn would reduce the traffic demand and congestion in the work zone, and the drivers who do not divert would be better prepared for the conditions ahead.

Changeable Message Signs Displaying Courteous Driver Messages

Changeable message signs may display messages that are intended to reduce aggressive driving behavior by advising or reminding drivers to be courteous. Reducing the amount of aggressive driving in advance of lane closures could increase the safety and efficiency of traffic operations in the merge area by reducing the frequency of forced merges and improving the uniformity of travel flow.

Public Information Campaign

The public information campaign proposal is based on the presumption that many drivers are unaware of the potential hazards of traveling through work zones. It assumes that if drivers are aware of the potential hazard and know how to drive properly through work zones, then they will drive more carefully through them. More careful drivers would result in less speeding and aggressive driver behavior, which in turn would improve the safety and efficiency of traffic flow in work zones.

No Passing Lines in Closed Lane

A major cause of driver irritation and erratic maneuvers is the use of the closed lane as a passing lane. Some drivers merge into the open lane at the last possible moment in order to get ahead of the vehicles in the slower moving open lane. Placing no passing lines in the closed lane is intended to eliminate this problem by making the late merge illegal.

Treatment to Discourage Use of Closed Lane

A proposed treatment to discourage the use of the closed lane is shown in Figure 3-5. It is composed of pavement markings, signing, and rumble strips which are intended to encourage drivers to merge to the open lane early and prohibit them from using the closed lane to pass.

Indiana Lane Merge

The Indiana Department of Transportation has developed and field tested the dynamic no-passing zone illustrated in Figure 3-6. It is called the "Indiana Lane Merge," which is intended to encourage drivers to merge into the open lane early and prohibit them from using the closed lane to pass. It uses sonic detectors to determine the presence of a queue of vehicles standing in the open lane. The detectors are mounted on DO NOT PASS signs with two flashing strobes and WHEN FLASHING supplementary plates. The signs are installed adjacent to the closed lane at ¼- to ½-mile intervals. When stopped vehicles are detected in the open lane at a sign, a signal is transmitted to the next upstream sign to turn on its flashing strobes. When vehicles are moving again, the strobes are shut off. In this way, the length of the no-passing zone is tailored to the length of congestion present.

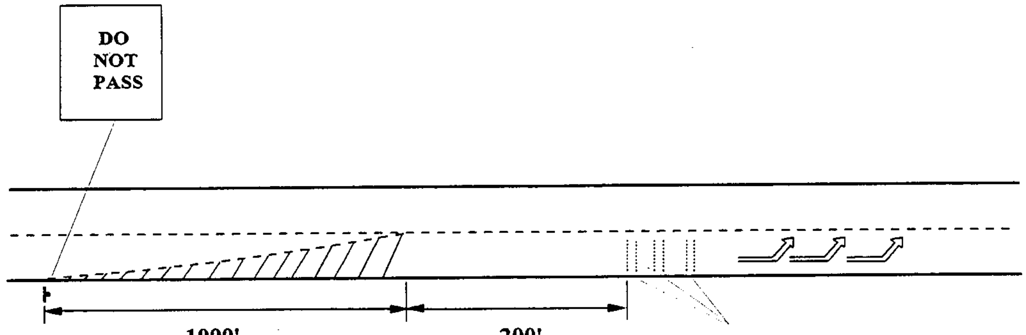


FIGURE 3-5 Treatment to Discourage Use of Closed Lane.

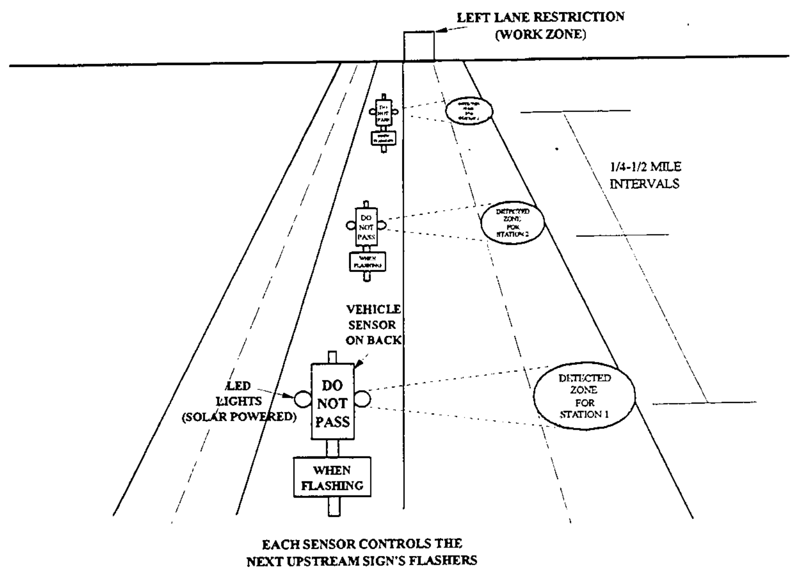


FIGURE 3-6 Indiana Lane Merge.

Speed Monitoring Display

Speed monitoring displays are used to slow traffic by advising drivers in real-time that they are traveling above the speed limit. The speed monitoring displays used by South Dakota and Virginia, which are shown in Figure 3-2 and 3-3, have been found to be effective in reducing excessive speeds in work zones.

SURVEY OF STATES

A survey of states was conducted to identify any innovative systems being used, tested, or considered by state highway agencies at lane closures on rural interstate highways. An e-mail requesting information on any such systems was sent to FHWA division offices by Frank Doland, Research Engineer, FHWA Nebraska Division. The responses indicated that innovative systems are being used, evaluated, or considered in eight states. A brief description of these systems follows.

Arizona

Arizona Department of Transportation uses CMSs and arrow boards to advise drivers of lane closures on rural interstate highways. However, the information presented on the CMSs is not based on real-time assessments of traffic conditions in the work zones.

California

California Department of Transportation is considering the use of a new product called ADAPTIR. This system monitors traffic flow and presents real-time messages to drivers on CMSs regarding traffic conditions ahead. A demonstration of the system is planned.

Indiana

Indiana Department of Transportation developed the Indiana Lane Merge, which is described above and shown in Figure 3-6. The system was field tested during the 1997 construction season. The system was found to smooth the merging operations. Drivers merged when they were supposed to merge and flow in the open lane was uniform with very few rear-end accidents. However, it did not increase throughput, and the results of a simulation study by Purdue University indicate that travel times are longer *(11)*. The field tests indicated that some additional space between the lane closure tape and the first DO NOT PASS sign upstream should be increased to provide adequate room for enforcement. It was also determined that the spacing of the signs should be logarithmic instead of uniform in order to account for the reduction in speed as traffic approaches the lane closure. Preliminary benefit-cost estimates indicate that implementation of the system is justified at lane closures where the capacity of the single lane will be exceeded at least 15 to 20 times per week. Indiana Department of Transportation is planning to continue testing the system during the 1998 construction season.

Iowa

Iowa Department of Transportation developed and tested a "Smart" Work Zone at a lane closure on I-80 in eastern Iowa during the 1997 construction season. The system is intended to improve safety in work zones by warning drivers about traffic conditions, increasing capacity, and providing traffic information. The system includes CMSs, highway advisory radio, and incident detection units. The layout of the system is illustrated in Figure 3-7.

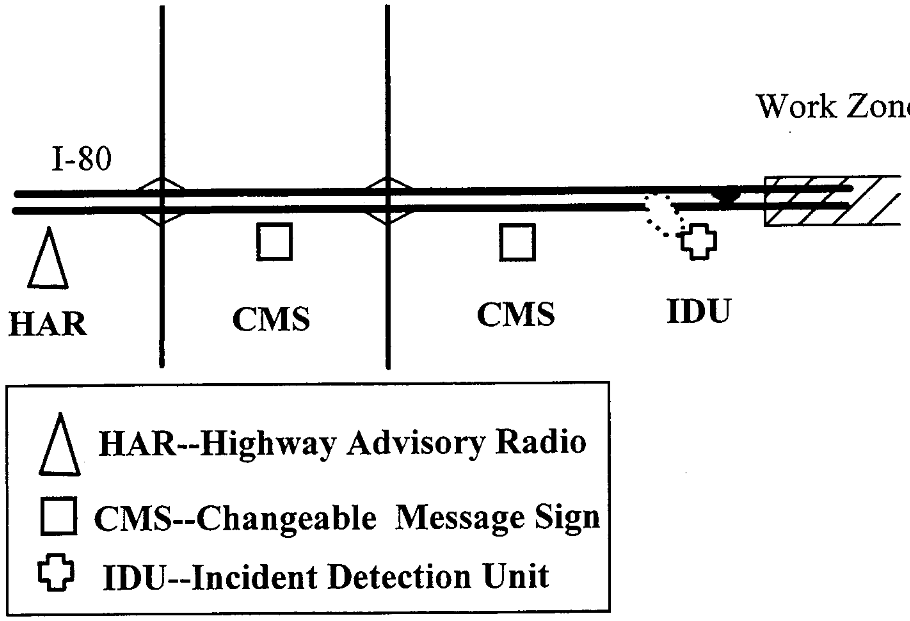


FIGURE 3-7 Iowa "Smart" Work Zone.

When congestion is detected, the system automatically notifies authorities and activates the appropriate highway advisory messages on the CMSs and highway advisory radio. The messages warn drivers about stopped traffic, congestion, and detours. The results of a field evaluation of the system have not been reported.

Maryland

Maryland State Highway Administration in cooperation with the FHWA is conducting a study on "Condition-Responsive, Work Zone Traffic Controls." The 5-year study, which began in 1993, is being conducted by Scientex Corporation. The purpose is to develop and evaluate condition-responsive, work zone traffic control devices and operations to be used in long-term construction zones. The typical layout of the system is shown in Figure 3-8. The system monitors traffic flow at a number of locations in advance of the work zone. Based on traffic conditions, the system uses CMSs and highway advisory radio to advise drivers about operating speeds, lane closures, and congestion ahead and to recommend diversion to alternate routes. The equipment has been designed and tested. Evaluation of the operational effects of the system is planned for the 1998 construction season.

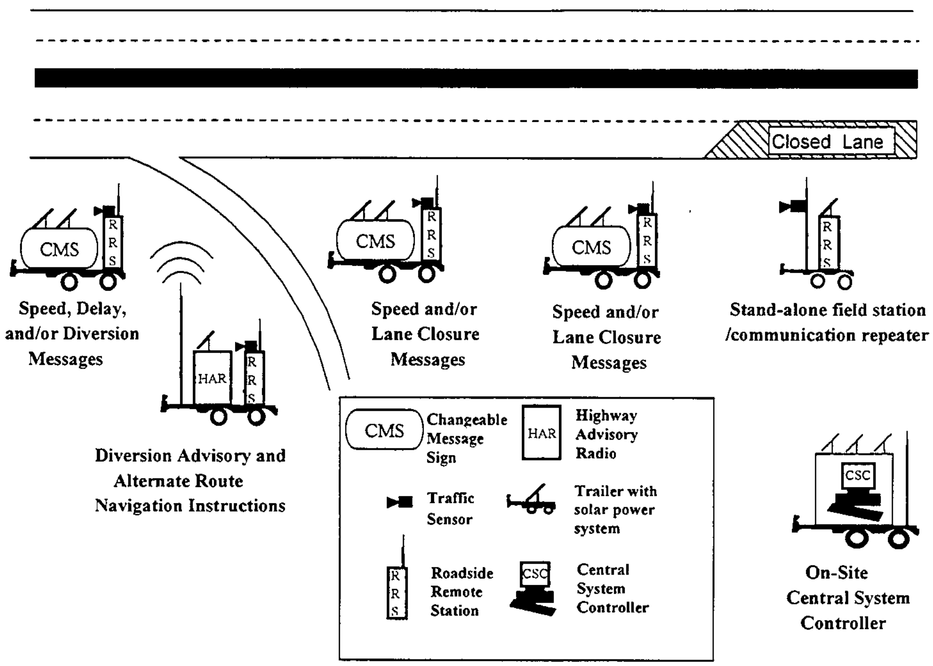


FIGURE 3-8 Maryland Work Zone Traffic Control System.

Minnesota

Minnesota Department of Transportation has developed an advanced portable traffic management system in partnership with FHWA and ADDCO Manufacturing Inc. The system is designed to transmit video surveillance and traffic flow data of operations in a work zone to a traffic management center. The components of the system are shown in Figure 3-9. Based on the information received, operators at the traffic management center activate appropriate messages on CMSs in advance of the work zone to warn drivers about conditions ahead.

Operational tests of the system were conducted during the 1996 and 1997 construction seasons. The results of the evaluation indicated that the system produced more orderly flow through the work zones *(12)*. About seven percent increase in capacity was observed. Also, the variability in traffic speeds within the work zones was reduced by 70 percent, and the average speed of vehicles approaching the work zones was reduced by 9 mph.

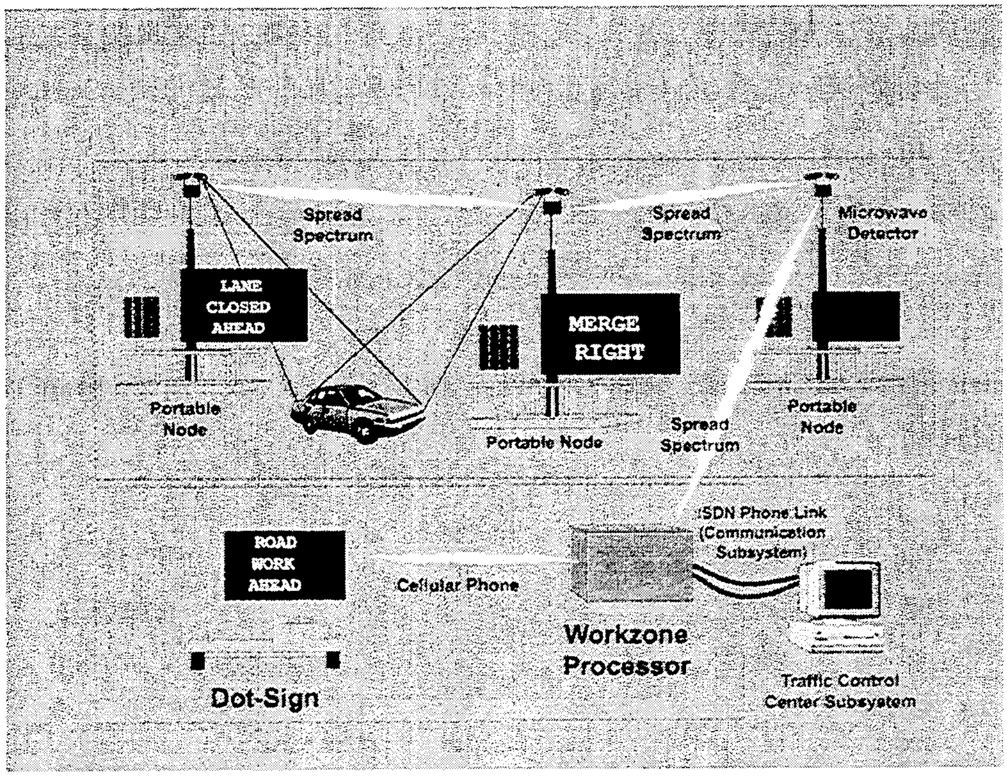


FIGURE 3-9 Minnesota Advance Portable Traffic Management System.

Ohio

Ohio Department of Transportation has been investigating several possible solutions to the problems associated with lane closures on rural interstate highways. The solutions, which are described below, range from installing additional advance warning signs to intelligent transportation systems.

Additional Signing

The primary action taken by the Ohio Department of Transportation has been to place additional signing in advance of the work zones to alert drivers and reduce the element of surprise. Signs with messages ROAD CONSTRUCTION AHEAD, LEFT/RIGHT LANE CLOSED AHEAD, and WATCH FOR STOPPED TRAFFIC, with appropriate distance plates and flashing warning lights, are placed on both sides of the roadways several miles in advance of the work zone at approximately one-mile intervals. The use of these signs and the distances in advance of the work zone are determine at the discretion of the design engineer. Portable CMSs are also used in some cases.

Narrow Lanes

During the 1998 construction season, the Ohio Department of Transportation is planning to experiment with narrow lanes to slow traffic in advance of the work zone. The narrow lanes will be created with pavement markings.

Always Closing Left Lane

Currently, the standard practice of the Ohio Department of Transportation is to close the left lane on interstate projects that require median crossovers. The plan is to extend this practice to lane closures for consistency.

Indiana Lane Merge

Ohio Department of Transportation is planning to try the Indiana Lane Merge at two or more work zones during the 1998 construction season. The Indiana Lane Merge is described above and shown in Figure 3-6.

Late Merge

Because of the friction between the early and late mergers in advance of lane closures, the Ohio Department of Transportation decided to study the Late Merge concept. The objective of the concept is to reduce friction between early and late mergers and increase the capacity of the merging operation by encouraging all drivers to be late mergers. The Late Merge, which was developed by the Pennsylvania Department of Transportation, is illustrated in Figure 3-10. Approximately two miles in advance of the lane closure, USE BOTH LANES TO MERGE POINT signs are placed on both sides of the roadway. These signs are repeated at about one mile in advance of the lane closure. These signs are followed by ROAD WORK AHEAD and advance lane closed signs. The, MERGE HERE TAKE YOUR TURN signs are placed about 500 feet before the taper.

The Late Merge was field tested at two work zones in 1991 *(13)*. Contrary to expectations, there was only a slight increase in late mergers at one site and a reduction in late mergers at the other site. Flow rates at the merge point increased from 1,700 to 2,100 vph at the site which showed a slight increase in late mergers. Flow rate data was not collected at the second site. Media reaction to the concept was positive; however, driver attitudes were not surveyed. It was concluded that the drivers did not understand or disregarded the signing; and therefore, work zone congestion and delay would only be slightly reduced by the Late Merge.

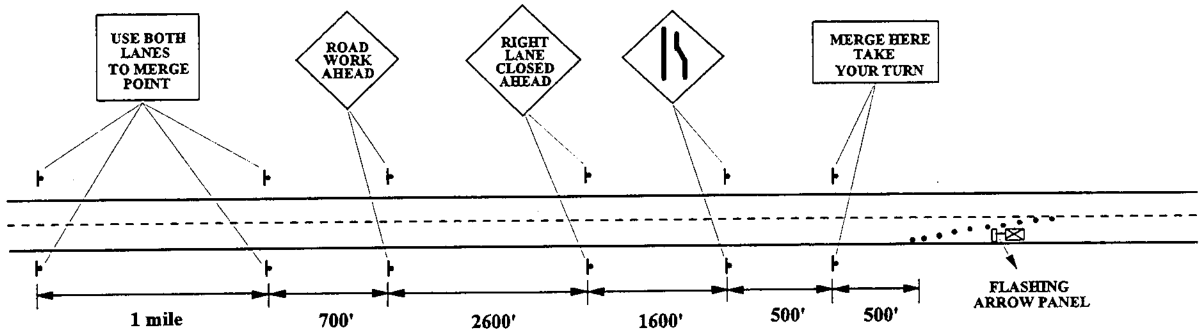


FIGURE 3-10 Late Merge System.

Equal Access Merge

The Equal Access Merge was a concept proposed to the Virginia Department of Transportation by a retired professional design engineer in 1996. The concept is illustrated in Figure 3-11. Instead of requiring vehicles in the closed lane to merge with vehicles in the open lane, vehicles in both lanes are advised to merge with each other at a designated merging point. The Virginia Department of Transportation utilized the microscopic Freeway Simulation (FRESIM) computer model to evaluate the effectiveness of the system. The results of the simulation indicated a slight increase in the capacity of the merge point; however, it was concluded that the idea was not practical. The Ohio Department of Transportation is reviewing the concept and may field test it during the 1998 construction season.

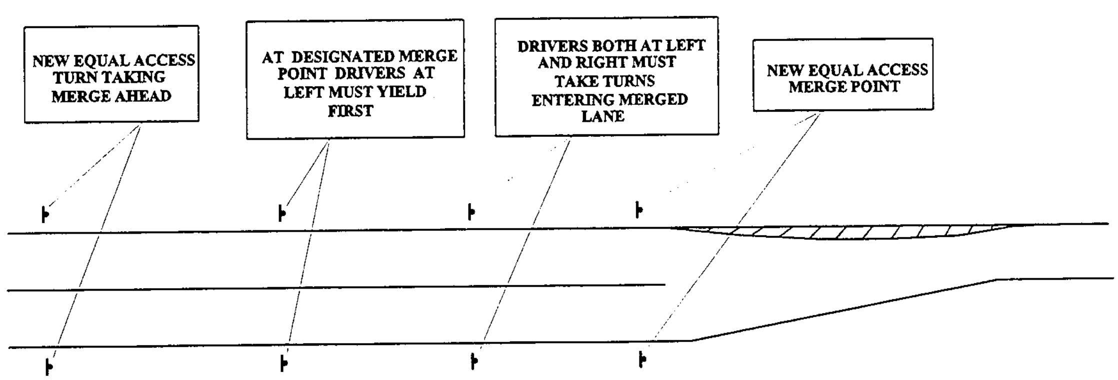


FIGURE 3-11 Equal Access Merge.

Travel Time Prediction System for Work Zones

Ohio Department of Transportation is sponsoring research conducted by the University of Cincinnati to develop a travel time prediction system for work zones. The system is designed to provide drivers with travel time information in advance of and through the work zone. It is a portable real-time system that uses roadway detectors to measure volumes and occupancy at several stations. These data are transmitted by radio communications to a personal computer which analyzes the data, predicts travel times, and activates travel time messages which are displayed on strategically located CMSs in advance of the work zone. The system was tested at a work zone on I-70 in east central Ohio in 1997. The system apparently worked well except for some communication problems; however, an evaluation of the operational effects has not been reported. More field tests are planned for the summer of 1998.

Pennsylvania

As mentioned previously, the Late Merge, which is shown in Figure 2-10, was developed by the Pennsylvania Department of Transportation. The system is intended to reduce the friction between early and late mergers and increase the capacity of the merging operation by encouraging all drivers to remain in their lanes until the merge point. This is not standard practice, but it is used regularly in work zones on rural interstate highways in some districts. No problems have been reported with its use, and it seems to be well received by drivers. A study of its operational effects found that it increased the capacity of the merging operations by as much as 15 percent *(14)*.

SUMMARY

Early studies found in the literature indicate that the use of CMSs placed about 0.75 miles in advance of the work zone and advising drivers of speed and lane closures was an effective method to increase the frequency of early merging and reduce speeds at the merge point. Computer simulations reported in the literature suggest that early merging of traffic in advance of lane closures may increase travel times, especially at higher traffic volumes. The literature also indicates that speed monitoring displays have been effective in reducing excessive speeds in work zones.

The brainstorming session identified several problems associated with lane closures at work zones on rural interstate highways. These problems included: speeding, friction between early and late mergers, high accident potential during congestion, difficulties of law enforcement, and limited maneuverability of trucks. The solutions generated to address these problems included: (1) providing information on traffic conditions in work zones at rest areas, fuel stops, and on advance CMSs, and (2) system treatments to encourage early merging and reduce speeding.

The survey of states revealed many innovative systems. California, Iowa, Maryland, Minnesota, and Ohio are developing and testing "smart" work zones, which feature the automated surveillance of traffic conditions in the work zone and the activation of CMS and highway-advisory-radio messages to drivers advising them about conditions ahead and the availability of alternative routes. These are still undergoing field testing, and evaluations of their effects on traffic operations are not complete.

Other states have developed systems that are focused on improving the merging operations. The Indiana Lane Merge and the additional signing used by Ohio are designed to encourage early merging. Field tests of these systems indicate that they encourage early merging and smooth merging operations. However, a computer simulation study of the Indiana Lane Merge indicated that throughput is not increased and travel times are longer, especially at higher traffic volumes. On the other hand, Pennsylvania's Late Merge and Virginia's Equal Access Merge are designed to eliminate the friction between early and late mergers by encouraging drivers to stay in their lanes until the merge point. Field tests of the Late Merge in Ohio and Pennsylvania found that the system provided increases in the capacity of merging operations of about 15 to 25 percent. Simulation studies of the Equal Access Merge indicated only slight increases in capacity.

The alternative work zone control strategies identified in this research are summarized in Table 3-1. The traffic control functions performed by these strategies are: merge control, speed control, and traffic diversion. Of the seven merge-control strategies, only the Indiana Lane Merge and "smart" work zone provide real-time information and require communications and traffic detection equipment. Among the six speed-control strategies, the speed monitoring display and "smart" work zone are the only ones providing real-time information and requiring communications and traffic detection hardware. Both of the traffic-diversion strategies (*i.e.*, "smart" work zone and information at rest areas) require real-time display, communications, and traffic detection hardware. The "smart" work zone is the only strategy capable of performing all three control functions (*i.e.*, merge control, speed control, and traffic diversion).

TABLE 3-1 Alternative Work Zone Control Strategies.

Strategy	Function				Hardware		
	Merge Control		Speed Control	Traffic Diversion	Real-Time Display	Com-munica-tions	Traffic Detection
	Early	Late					
Iowa Weave			✔				
Longer Speed Transition Zone			✔				
Narrow Lanes			✔				
Speed Monitoring Display			✔		✔	✔	✔
Advance CMSs	✔		✔				
Always Close Left Lane	✔						
Treatment in Closed Lane	✔						
Indiana Lane Merge	✔				✔	✔	✔
Equal Access Merge		✔					
Late Merge		✔					
"Smart" Work Zone	✔	✔	✔	✔	✔	✔	✔
Information at Rest Areas				✔	✔	✔	✔

Chater 4

SIMULATION OF ALTERNATIVES

A computer simulation study was conducted to evaluate the operational performance of the alterative work zone control strategies identified in the research, which are described in Chapter 3. The effects of the strategies on the merging operations in advance of the lane closure were the focus of the evaluation. The procedures, models, and results of the simulations of the speed-control, merge-control, and traffic-diversion strategies are presented in this chapter.

MODELS

Three computer models were used to conduct the simulation study. Two of the models were the microscopic freeway simulation model (FRESIM) and the macroscopic freeway simulation model (FREFLO) developed by the FHWA. The third model was the work zone simulation model (WZSIM) developed by the research team. The FRESIM and WZSIM models are microscopic models, which means that they model the movements of individual vehicles. FREFLO is a macroscopic model, which means that it represents traffic flow in terms of aggregate measures (*i.e.*, speed, flow, and density) of traffic flow on each roadway segment.

FRESIM

FRESIM is a microscopic freeway simulation model. It is capable of simulating vehicle behavior under most of the prevailing freeway conditions including: variations in grade, curvature, and superelevation; one- to five-lane freeways with one- to three-lane ramps and one- to three-lane inter-freeway connectors; lane drops; auxiliary lanes; and lane blockage incidents. Work zones are simulated using the model's lane-blockage-incident capability. Therefore, the variety of work zone control strategies that can be simulated with FRESIM is limited. In this study, FRESIM was used to simulate the Indiana Lane Merge. The User's Manual of the Corridor Microscopic Simulation Model provides a detailed description of FRESIM *(15)*.

FREFLO

FREFLO is a macroscopic freeway simulation model. It simulates traffic flow in terms of the speed-flow-density relationships defined for each freeway section. Therefore, it is suited to the evaluation of less detailed strategies in terms of the specification of roadway geometric and traffic control measures. In this study, FREFLO was used to simulate the traffic-diversion strategies. The user reference guide for FREFLO provides a detailed description of the model *(16)*.

WZSIM

WZSIM is a microscopic, interstate highway, work zone simulation model. It was developed by the research team because existing models are not able to simulate in an explicit manner all of the work zone control strategies identified in this research. The model simulates vehicle behavior in response to the proximity of other vehicles in the traffic stream, lane configuration, and the speed and merge control features of the work zone control strategy. Vehicle movements are described by two fundamental rules: (1) the car-following rule and (2) the lane-changing rule. Both rules incorporate a set of possible actions that may be taken by a motorist in response to changes in the driving environment. The general form of such a rule is:

$$response(t + \tau) = \varphi\big(stimuli(t)\big) \qquad (4\text{-}1)$$

where, response (t+τ) = the action taken by a driver at time $t+\tau$
stimuli (t) = any change in the driving environment observed by the driver at time t
τ = the drivers's reaction time
φ (.) = a response function

Although each vehicle is capable of accelerating, decelerating and lane changing, they are assumed to perform any of these maneuvers only when forced by another vehicle (*e.g.*, speed difference, minimum headway) or in response to external constraints (*e.g.*, traffic control, approaching lane closure). The longitudinal movement of vehicles within a time increment Δt is described by the equations of motion:

$$\begin{aligned} x_i(t+\Delta t) &= x_i(t) + v_i(t)\Delta t \\ v_i(t+\Delta t) &= v_i(t) + a_i(t)\Delta t \end{aligned} \qquad (4\text{-}2)$$

where, $x_i(t)$ = distance of vehicle i from the upstream boundary of the model at time t (feet);
$v_i(t)$ = speed of vehicle i at time t (ft/s);
$a_i(t)$ = acceleration rate of vehicle i at time t (ft/s^2);
Δt = simulation time step (s).

The model setup of WZSIM is shown in Figure 4-1. It consists of three different segments: (1) the highway section with "normal" conditions prior to the first warning sign pertaining to the lane closure; (2) a merge area located between the first warning sign and the beginning of the lane taper; and (3) a single lane section along the work area. Traffic operations in the road segment with "normal" conditions are undisturbed in that any lane changing is controlled only by the actual traffic conditions and the drivers' personal preference. Lane changes in the merge area are primarily controlled by traffic control devices encouraging vehicles in the closed lane to merge into the open lane. Vehicle movement in the single-lane segment is longitudinal and simply organized by a car following rule. In this study, WZSIM was used to simulate speed-control and merge-control strategies.

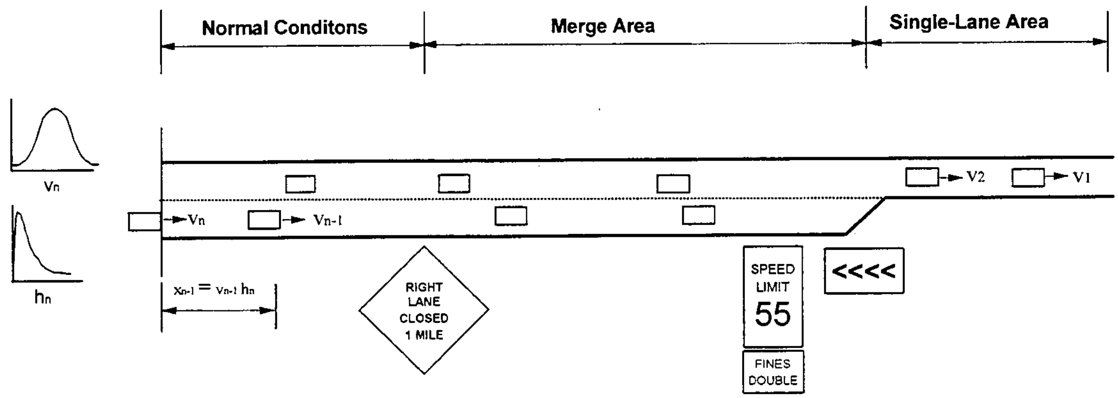


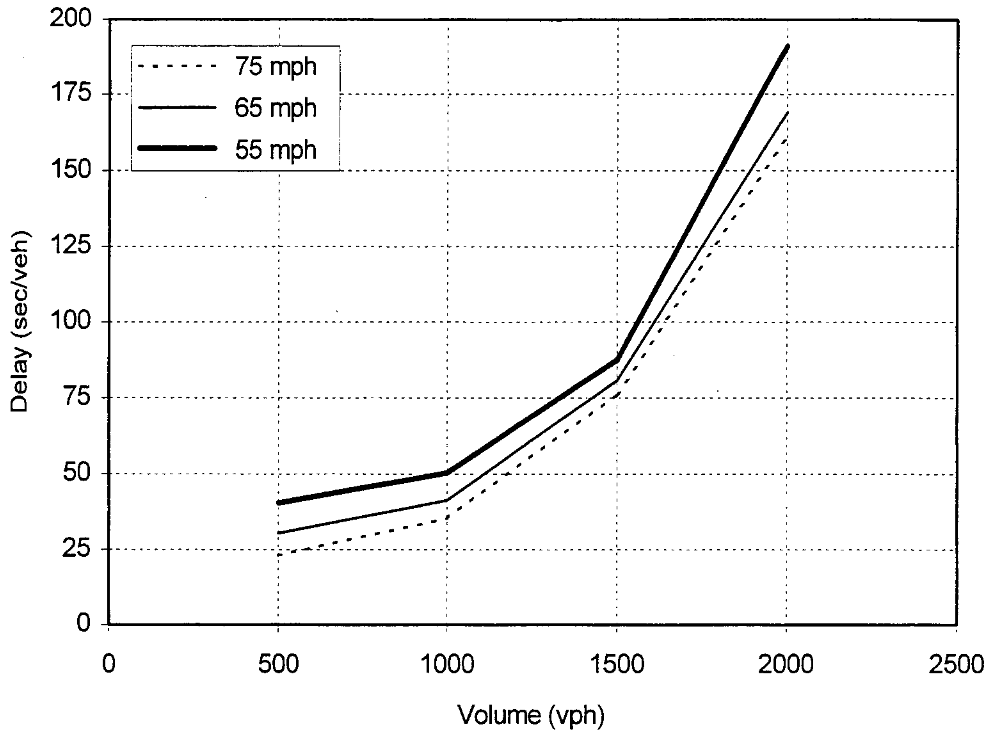
FIGURE 4-1 Work Zone Simulation Model Setup.

SPEED-CONTROL STRATEGIES

There are three types of speed-control strategies based on their objectives. The first type (*i.e.*, Iowa Weave, longer speed transition zone, and narrow lanes) is designed to slow traffic in advance of the lane closure. The second type (*i.e.*, advance CMSs and "smart" work zones) is designed to advise drivers about speeds appropriate to conditions ahead. The third type is the speed monitoring display, which is intended to increase driver compliance with the speed limit. However, with respect to the effects on the merging operations in advance of the lane closures, the basic issue addressed by the simulation study was the effect of speed on the merging operations. It was not the purpose of the simulation study to determine the effects of these strategies on speed.

The WZSIM model was used to investigate the effect of speed on the merging operations. Three speed-control alternatives were considered. The first alternative was the speed control associated with the NDOR Merge for a typical lane closure shown in Figure 3-4. The plan has 75-mph SPEED LIMIT signs at approximately 8,500 feet in advance of the lane closure taper and 55-mph SPEED LIMIT signs at 500 feet in advance of the taper. The second alternative was the longer speed zone transition, which was suggested in the brainstorming session. This alternative is the same as the first alternative except that the 75-mph SPEED LIMIT signs are replaced by 65-mph SPEED LIMIT signs as described in Chapter 3. The third alternative was the same as the first two alternative except that 55-mph SPEED LIMIT signs are placed at approximately 8,500 feet in advance of the taper instead of the 75-mph or 65-mph SPEED LIMIT signs.

The simulation results are shown in Figure 4-2. The results indicate that the lower speed limits in advance of the lane closure increase delay, because the vehicles are required to travel at slower speeds. Also, the throughput is slightly less for the lower speed limits, because the vehicles are required to travel at slower speeds. However, the results indicate that the primary effect of a lower speed limit is an increase in delay of about 10 to 30 seconds per vehicle depending on the volume.



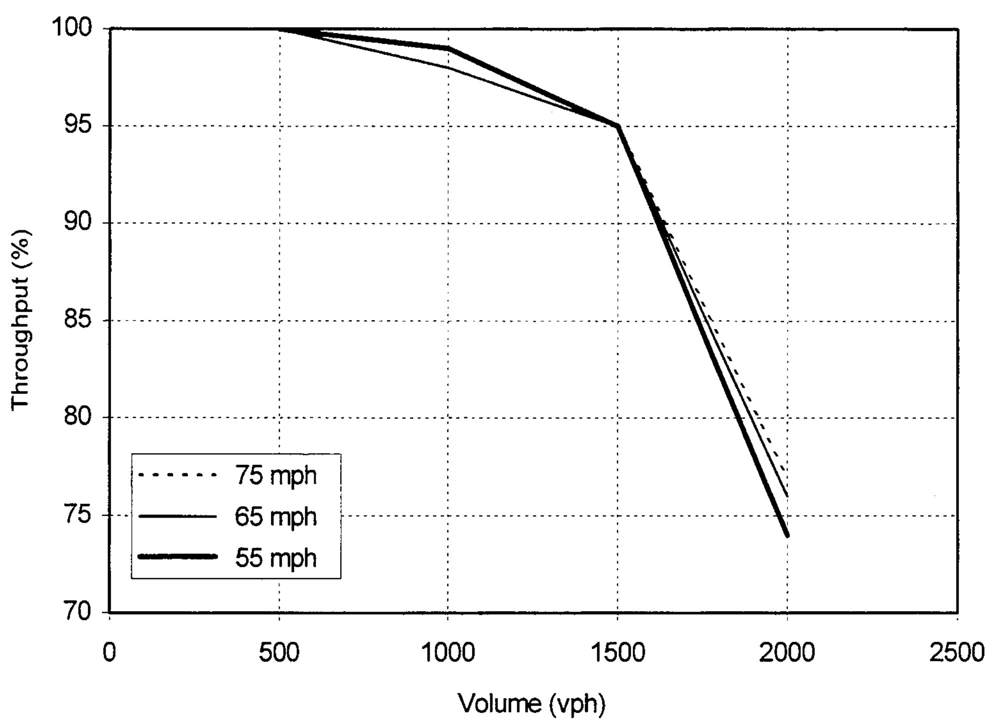


FIGURE 4-2 Speed-Control Strategy Simulation Results.

WZSIM assumes that the vehicles comply with the speed limits imposed by the speed-control strategies. If this is possible to achieve by simply posting the SPEED LIMIT signs and normal enforcement, neither of the other two speed-control strategies designed to slow traffic (*i.e.*, Iowa Weave and narrow lanes) nor the speed monitoring displays designed to increase speed limit compliance would be needed to achieve the effects of lower speed limits.

MERGE-CONTROL STRATEGIES

The merge-control strategies are of two basic types. One type encourages drivers to merge early (*i.e.*, further in advance of the lane closure). The other type encourages drivers to merge late (*i.e.*, at a merge point near the lane closure). As indicated in Table 3-1, the early-merge control strategies include: (1) advance CMSs, which have traditionally been used to encourage early merging *(4)*, although they could also be used to encourage late merging; (2) always close the left lane, which gives the drivers *a priori* knowledge enabling them to merge earlier; (3) treatment in the closed lane, which is designed to discourage drivers from using the closed lane; and (4) Indiana Lane Merge, which encourages early merging by prohibiting passing in the closed lane. The late-merge control strategies are the Equal Access Merge and the Late Merge. The "smart" work zone is capable of both types of merge control. FRESIM was used to evaluate the operational effects of the Indiana Lane Merge, while WZSIM was used to simulate the other early-merge control strategies as well as the late-merge control strategies.

Indiana Lane Merge

The Indiana Lane Merge is a form of early-merge control. It features a dynamic no-passing zone which is intended to encourage drivers to merge into the open lane early by prohibiting them from passing in the closed lane. The length of the no-passing zone is adjusted automatically based on the level of congestion in the open lane. As illustrated in Figure 3-6, it uses sonic detectors to determine the presence of a queue of vehicles standing in the open lane. The detectors are mounted on DO NOT PASS signs with two flashing strobes and WHEN FLASHING supplementary plates. The signs are installed adjacent to the closed lane at ¼- to ½-mile intervals. When stopped vehicles are detected in the open lane at a sign, a signal is transmitted to the next upstream sign to turn on its flashing strobes. When vehicles are moving again, the strobes are shut off. In this way, the length of the no-passing zone is tailored to the length of congestion present.

The operation of the Indiana Lane Merge was simulated with FRESIM. The system simulated had DO NOT PASS signs installed at ½-mile intervals, beginning ½-mile in advance of the lane closure and extending upstream for a distance of 3 miles. In order to simulate the dynamic nature of the Indiana Lane Merge, it was necessary to utilize the animation output of FRESIM to monitor the traffic flow conditions in the merge area and interrupt the simulation run when the presence of congestion in the open lane next to each sign changed. When a queue of vehicles standing in the open lane reached a DO NOT PASS sign location, a lane blockage incident was created in the closed lane at the next upstream sign location, which prohibited vehicles from using the closed lane between the upstream sign location and the lane closure. The time of the incident was recorded, the model input was modified accordingly, and the simulation was continued. When a queue in the open lane next to a DO NOT PASS sign location cleared, the lane blockage incident at the next upstream DO NOT PASS sign location was removed, which allowed vehicles to use the closed lane. The time of the incident removal was recorded, the model input was revised accordingly, and the simulation was continued. This process was repeated until the simulation run had been completed.

In addition to the Indiana Lane Merge, FRESIM was used to simulate two other merge-control cases: (1) no merge-control strategy (*i.e.*, the current NDOR Merge in Figure 2-4) and (2) a constant ½-mile, no-passing zone in advance of the lane closure. In each case, simulation runs were made at three volume levels (1,000; 1,500; and 2,000 vph) and three truck percentages (10, 20 and 30 percent). The simulation results are shown in Figure 4-3.

The simulation results indicate that the Indiana Lane Merge increases throughput and reduces delay and lane changes when compared to the current NDOR Merge. At all volumes and truck percentages, the Indiana Lane Merge performed better than the current plan. In addition, the results indicate that the constant ½-mile, no-passing zone also performed better than the current plan at all volumes and truck percentages, although not as well as the Indiana Lane Merge at the higher volumes. The performances of the constant ½-mile, no-passing zone and the Indiana Lane Merge were the same at the lowest volume (1,000 vph), because the queue of vehicles standing in the open lane never reached the first DO NOT PASS sign location. Consequently, the two alternatives operated in the same manner at this volume level.

It must be noted that FRESIM assumes that all drivers in the closed lane comply with the no-passing restriction, which may not be realistic, especially in the case of the constant ½-mile no-passing zone. Also, experience in Indiana *(11)* did not indicate that the Indiana Lane Merge increased throughput or reduced delay. Furthermore, it must be remembered that it was not possible to model the Indiana Lane Merge directly. Instead, it was necessary to monitor the animation output during the simulation runs and interrupt them to effect the activation of the DO NOT PASS signs. Therefore, the results of these FRESIM simulations must be viewed with caution.

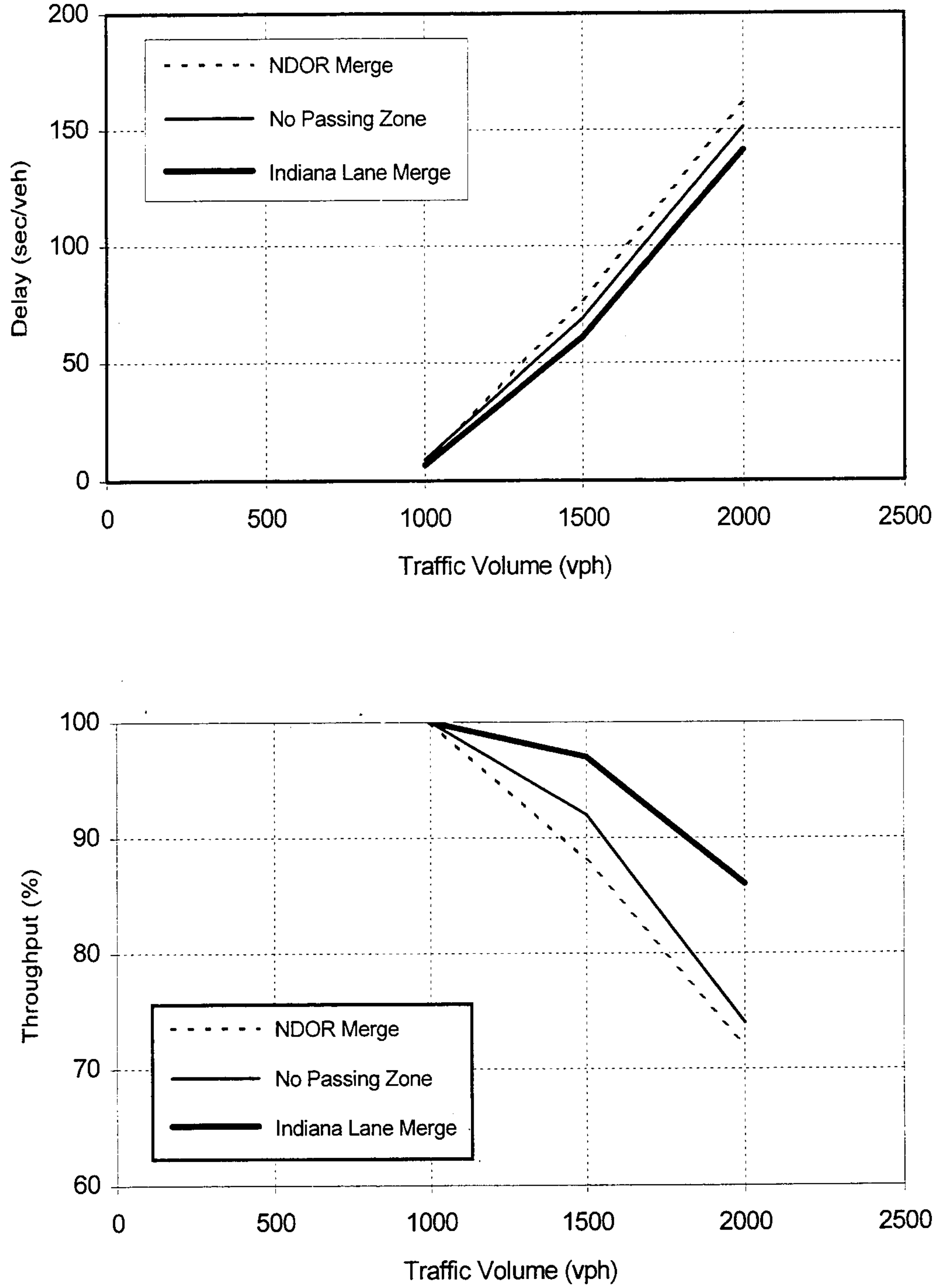


FIGURE 4-3 Indiana Lane Merge Simulation Results.

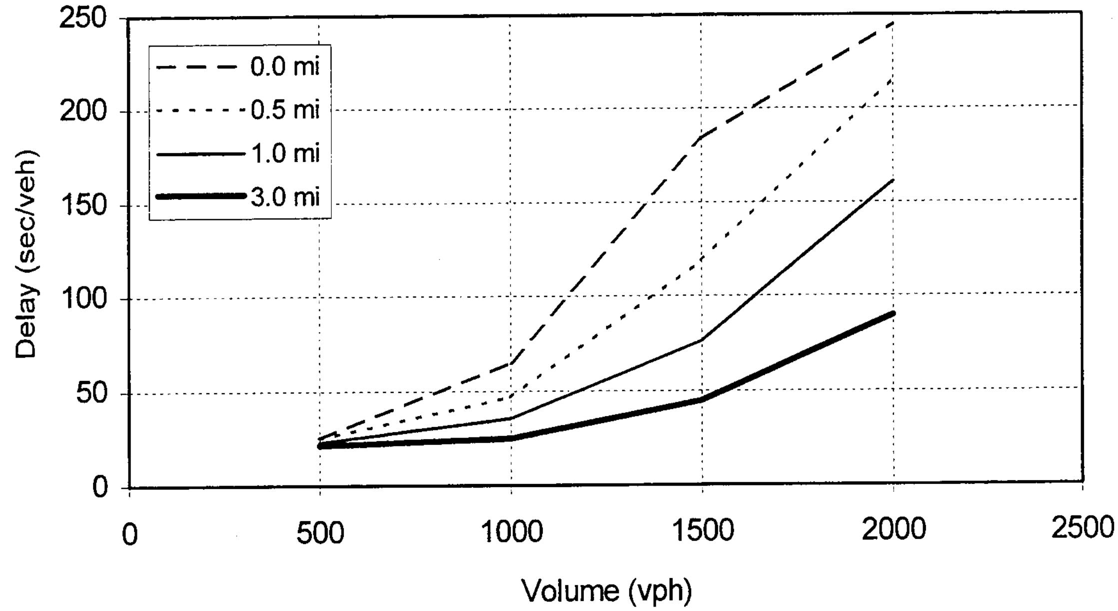
Other Early-Merge Control Strategies

The distance in advance of the lane closure at which drivers are first encouraged to merge into the open lane is a variable with the Indiana Lane Merge and "smart" work zone depending on the level of congestion. But, in the case of the other early-merge control strategies (*i.e.*, advance CMSs, always close the left lane, and treatment in closed lane) this distance is fixed. Previous research *(2)* found that advance CMSs encouraged early merging, and similar results were obtained by studies of the other two fixed, early-merge control strategies. Therefore, assuming that these strategies are equally effective in causing drivers to merge early, the objective of the simulation was to evaluate the operational effects of the distance in advance of the lane closure at which drivers are first encouraged to merge into the open lane.

The WZSIM model was used to simulate the fixed, early- merge control strategies. The point at which drivers were first encouraged to merge into the open lane was varied from zero to 3 miles at ½-mile intervals in advance of the lane closure taper. According to the WZSIM model, when vehicles in the closed lane reach this point, they immediately begin looking for an adequate gap and merge into the open lane as soon as possible. Simulation runs were conducted at traffic volumes of 500 to 2,000 vph at 500 vph intervals for each distance. The simulation results are shown in Figure 4-4.

The delay is reduced as the distance in advance of the lane closure is increased. In other words, the farther in advance drivers are informed about the lane closure, the less delay they experience. Also, the throughput is higher when drivers are advised of lane closures farther in advance. Drivers have more opportunities to merge into the open lane when they are given more advance notice of a lane closure. Therefore, they are less likely to be delayed in the closed lane, and a higher density and speed of traffic flow can be achieved in the open lane resulting in more throughput.

These results are consistent with the findings of the simulation of the Indiana Lane Merge, which in effect encourages merging farther in advance of the lane closure as traffic demand increases. However, it must be remembered that driver behavior used in WZSIM assumes that when vehicles in the closed lane reach the first notice of the lane closure, they immediately begin looking for an adequate gap and merge into the open lane as soon as possible. Although many drivers may behave in this manner, some do not. Therefore, the actual distances at which merging operations are optimal may be different than those indicated by the simulation results. The simulation results are only indicative of the operational effects that may be observed in the field.



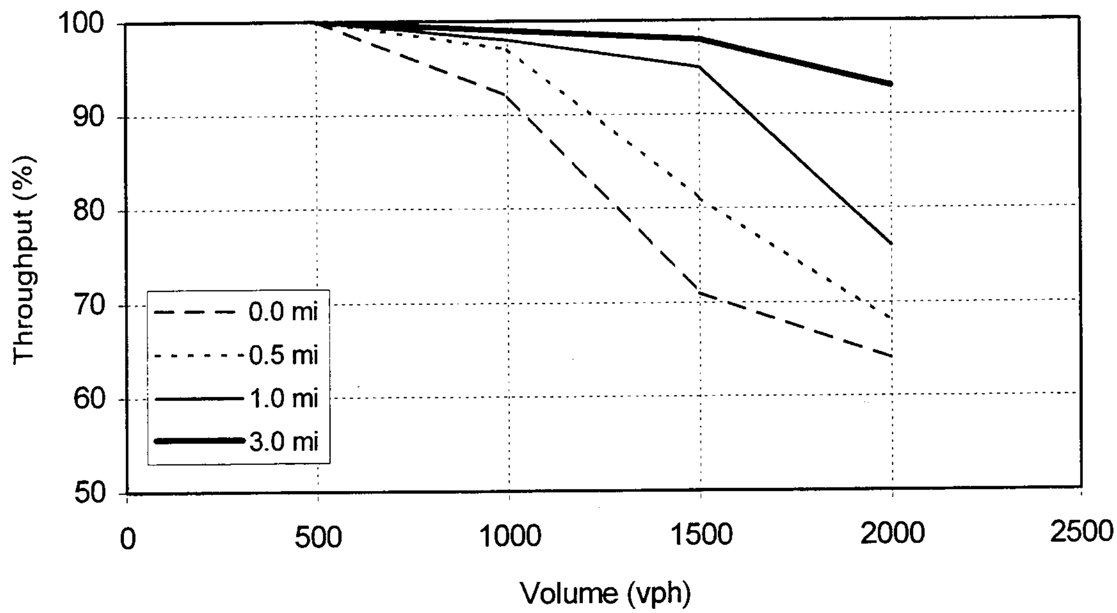


FIGURE 4-4 Other Early-Merge Control Strategy Simulation Results.

Late-Merge Control Strategies

The late-merge control strategies include the Equal Access Merge and the Late Merge, but the "smart" work zone is also capable of the late-merge control strategy. According to their descriptions in Chapter 3, the Equal Access Merge and the Late Merge are very similar. Therefore, one simulation study was conducted, and it was assumed that the results would be applicable to both strategies.

WZSIM was used to simulate the late-merge control strategies. Two sets of simulation runs were made. The first set of runs was for the NDOR Merge. In this case, the vehicles in the closed lane began trying to merge into the open lane when they reached the first "lane closed" sign one mile in advance of the lane closure. The second set of runs was for the Late Merge. The traffic control plan simulated was similar to the NDOR Merge, except that the lane closed signs were removed. In this case, all vehicles remained in their lanes until they reached the merge point at the beginning of the taper. When vehicles in both lanes arrived at the merge point at the same time they took turns entering the work zone. In both cases, simulation runs were made at four volume levels (500 vph; 1,000 vph; 1,500 vph; and 2,000 vph). The simulation results are shown in Figure 4-5.

At the lower traffic volumes (500 and 1,000 vph), there was no substantial difference in the performance of the two alternatives. However, at the higher volumes (1,500 and 2,000 vph), the Late Merge control strategy had less delays and higher throughput. The better performance of the Late Merge control strategy at the higher volumes is the result of the more uniform flow provided by the alternating merging pattern between the two lanes. These results suggest that a Late Merge control strategy should be implemented when volumes exceed a certain threshold.

TRAFFIC-DIVERSION STRATEGIES

Traffic-diversion strategies encourage drivers to avoid congestion in work zones by providing them with real-time information about traffic conditions ahead and the availability of alternative routes. The traffic diversion which results from such information reduces the traffic demand at the work zones, which in turn reduces the level and duration of congestion. The two traffic-diversion strategies identified in this research are the "smart" work zone and information at rest areas. The "smart" work zone displays the real-time information via CMSs and/or highway advisory radio transmitters deployed in advance of diversion points to alternative routes. The information-at-rest-areas strategy provides the real-time information via kiosks and/or highway advisory radio located at the rest areas.

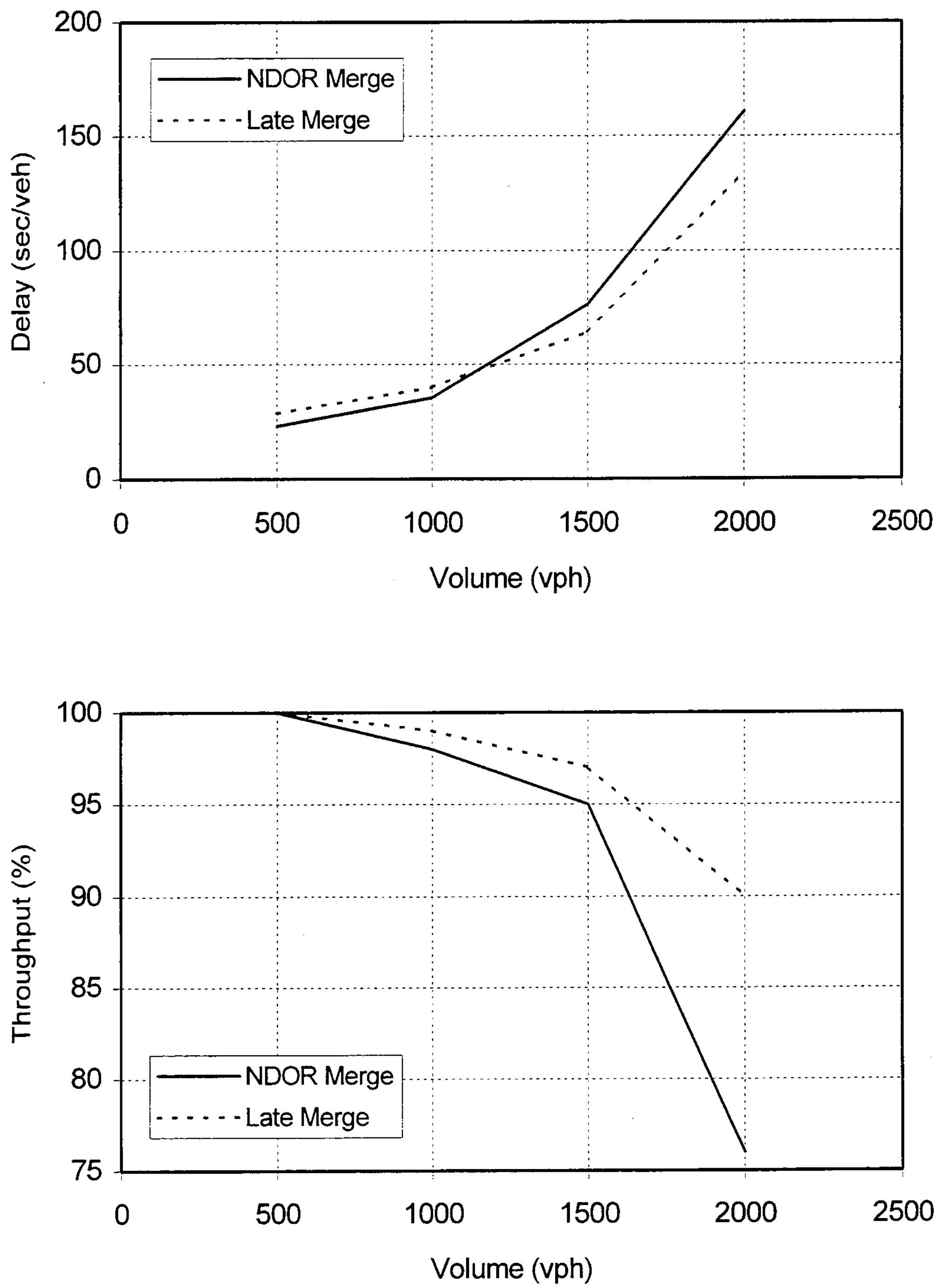


FIGURE 4-5 Late Merge Control Strategy Simulation Results.

The magnitude of the reduction in traffic demand depends on the nature of the congestion in the work zone. In the case of a major incident in the work zone requiring closure of the roadway and mandatory diversion, the amount of reduction would be 100 percent. However, if the roadway is not closed and the diversion is voluntary, the reduction in demand , or the amount of the diversion would depend on the credibility and timeliness of the information provided the drivers and the availability of suitable alternative routes. Based on the route-diversion effects of real-time traveler information found in the literature *(17)*, a 15-percent reduction in demand would be a reasonable estimate of the likely effects of voluntary route diversion. Where alternative routes are not available, some reduction in demand may still occur even though route diversion is not possible. This reduction in demand would be the result of temporal shifts in demand caused by drivers deciding to interrupt their travel and wait until the congestion in the work zones clears before continuing their trips. Others who receive information via CMSs or highway advisory radio along the roadway may decide to exit and wait at the next interchange before reaching the congestion at the work zones. Some drivers who receive the information at rest areas may decide to wait there. Although these drivers would still be delayed, they would not be exposed to the secondary accident risk associated with congestion.

The FREFLO model was used to simulate the traffic-diversion strategies. The simulation study was conducted for directional ADTs from 17,500 to 30,000 vpd at 2,500 vpd increments. For each ADT, the traffic flow at a single lane closed on a 4-lane freeway during a 24-hour period was simulated twice, once with traffic diversion and once without traffic diversion. The distribution of hourly volumes used in the simulation was the 1996 hourly volume distribution reported for the NDOR automatic traffic recorder station #45 on I-80 one mile west of the Aurora interchange. The hourly volumes had 35 percent trucks, which was assumed to be representative of rural interstate highways in Nebraska *(18)*. The capacity of the work zone was set at 1,500 vph *(19)*. *A* 15-percent reduction in the hourly volumes was used to represent the effects of traffic diversion.

The results of the simulation runs are shown in Figure 4-6. As expected, the delay with traffic diversion (*i.e.*, the reduced hourly volumes) is lower than the delay when there is no diversion. The reduction in delay due to diversion increases from zero at 17,000 vpd to about 16,000 vehicle-hours per day at 25,000 vpd. But, as the ADTs increases from 25,000 vpd to 30,000 vpd, the reduction in delay decreases considerably, to abut 4,000 vehicle-hours per day, because the number of hours during the day that the demand exceeds the capacity of the work zone with diversion is about the same as without diversion. For example, at 25,000 vpd, demand exceeds the capacity of the work zone during 11 hours of the day without diversion and only 4 hours with diversion. However, at 30,000 vpd, demand exceeds capacity during 13 hours without diversion and 11 hours with diversion. Therefore, the difference in delay with and without diversion is less at higher ADTs above 25,000 vpd.

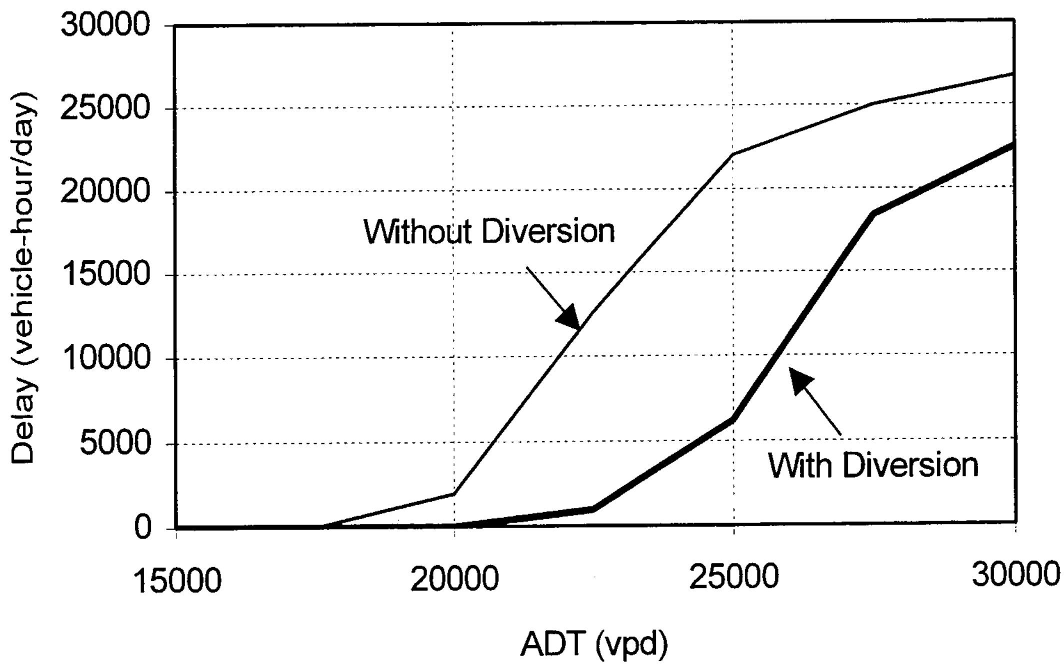


FIGURE 4-6 Traffic-Diversion Strategy Simulation Results.

The results of the simulation indicate that traffic-diversion strategies can provide substantial reductions in delay. However, it should be noted that these results do not account for the travel time of the diverted traffic on the alternative routes. Therefore, the travel time of the diverted traffic must be added to the delay shown for the traffic with diversion treatment in Figure 4-6. For example, at 22,500 vpd, the delay is about 12,500 vehicle-hours per day without diversion and 1,000 vehicle-hours per day with diversion, representing a reduction in delay due to diversion of 11,500 vehicle-hours per day. But, if the travel time of the diverted traffic on the alternative route is 6,000 vehicle-hours per day, the delay with diversion would be 7,000 vehicle-hours per day, representing a reduction in delay of 5500 instead of 11,500 vehicle-hours per day.

SUMMARY

The simulation study investigated the operational effects of the alternative work zone control strategies in terms of traffic delay and throughput. The strategies simulated were: (1) the NDOR Merge, (2) lower speed limits in advance of the lane closure in the NDOR Merge, (3) Indiana Lane Merge, (4) Early Merge, and (5) Late Merge. The simulation results for the strategies are summarized in Figure 4-7. In the case of the speed-control and early-merge control strategies, only results for the best alternatives (*i.e.*, the alternatives with the least delay and the highest throughput) are shown, which are the 65-mph speed-control strategy and the 3-mile early-merge control strategies.

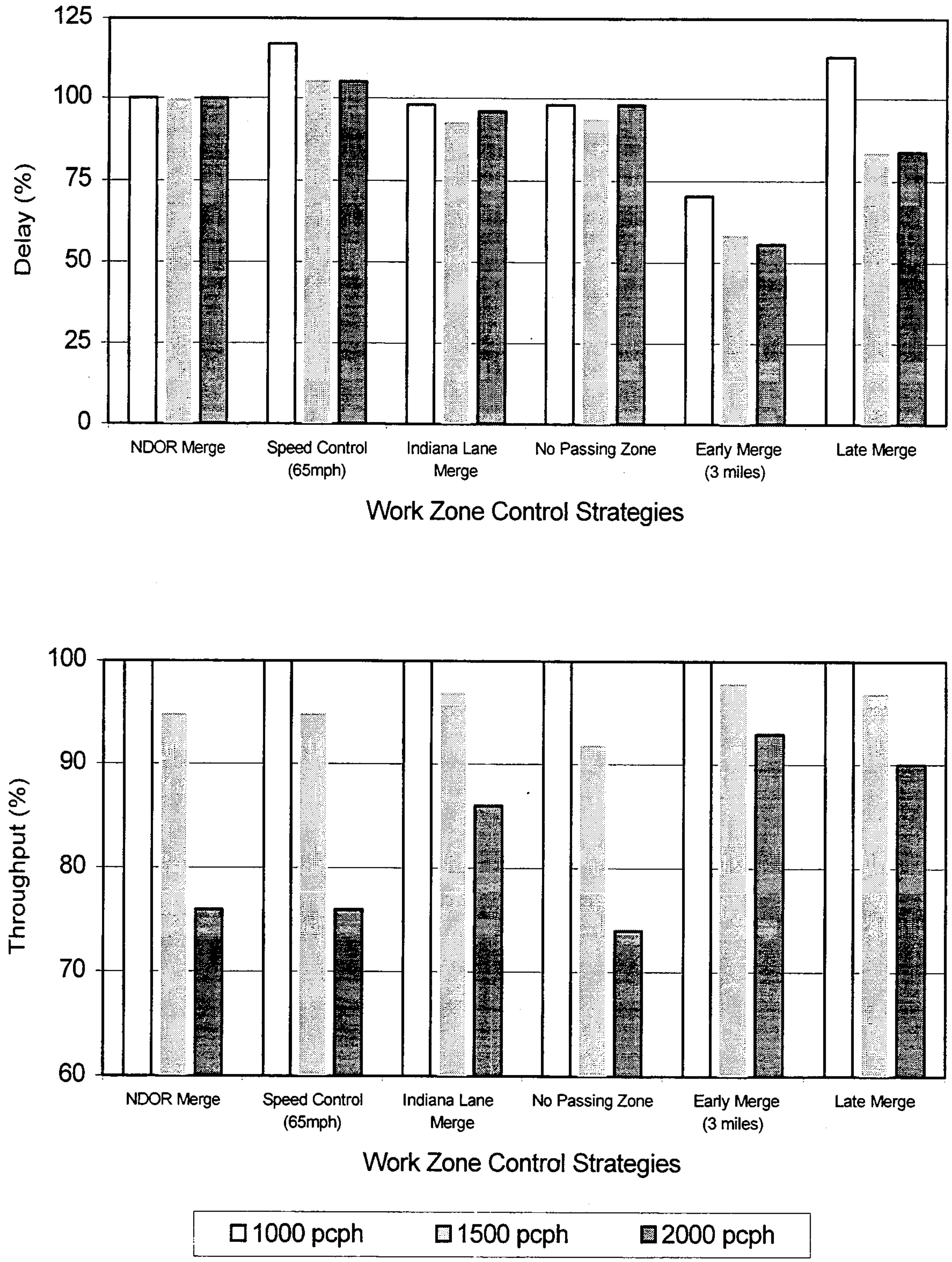


FIGURE 4-7 Summary of Simulation Results.

In Figure 4-7, the delay for each strategy is expressed as a percentage of the delay for NDOR Merge at three volume levels (1,000 vph; 1,500 vph; and 2,000 vph). The Early Merge causes less delay than the NDOR Merge at all three volume levels. It reduces delay by about 30 to 40 percent or more over the range of volumes. Although it slightly increases delay at the lowest volume (1,000 vph), the Late Merge causes about 20 percent less delay than the NDOR Merge at the two higher volumes (1,500 and 2,000 vph). The Indiana Lane Merge performed similarly to the NDOR Merge in terms of delay. However, the speed-control strategy causes more delay than the NDOR Merge at all three volumes levels. Therefore, based on delay, the Late Merge and the Early Merge are the best strategies according to the simulation results.

In Figure 4-7, the throughput for each strategy is expressed as a percentage of the traffic demand at three volume levels (1,000 vph; 1,500 vph; and 2,000 vph). The Indiana Lane Merge, Early Merge, and Late Merge provide higher throughput than the NDOR Merge at all three volume levels. These strategies increase throughput by about 15 to 20 percent at the highest volume level (2,000 vph). As expected, the speed control strategy provides no increase in throughput. Thus, in terms of throughput, the Indiana Lane Merge, Early Merge, and Late Merge are the best strategies according to the simulation results.

The traffic-diversion strategies provide substantial reductions in delay at higher traffic volumes as shown in Figure 4-6. However, they are not comparable to the speed-control and merge-control strategies on the basis of the results of the simulation study, because they do not impact directly the merging operation. Instead, they influence the traffic demand. It is important to note that since the traffic-diversion strategies and the other strategies are not mutually exclusive, the implementation of a traffic-diversion strategy would not prohibit the implementation of a speed or merge-control strategy, and vice versa.

Overall, the results of the simulation study indicate that the Indiana Lane Merge, Early Merge, and Late Merge provide more efficient traffic operations than either the NDOR work zone control strategy, or the lower speed limits in advance of the NDOR Merge. After reviewing these results and considering the availability of suitable study sites, the NDOR Project monitors selected the Indiana Lane Merge and the Late Merge as the two alternatives to be evaluated in the field. This decision was made because: (1) there were no suitable study sites for evaluating the three strategies in Nebraska during the 1998 construction season and (2) a search of study sites in other states found sites for the evaluation of the Indiana Lane Merge and the Late Merge, but none were found for the Early Merge.

Chapter 5

FIELD STUDIES OF SELECTED ALTERNATIVES

According to the research plan, the NDOR selected two of the alternative work zone control strategies evaluated in the simulation study in Chapter 4 for further study in the field. The two alternatives selected were the Late Merge and the Indiana Lane Merge. The procedures and results of these field studies are described in this chapter. Based on the results of these studies and the preliminary studies in Chapter 2, a comparison of the performance of these alternatives with that of the NDOR Merge is also presented.

MEASURES OF EFFECTIVENESS

The main traffic characteristics of interest included volume, speed, density and lane distribution; but drivers behavior and traffic conflicts were also studied. Table 5-1 summarizes the main data types collected during the field studies. These data were required to determine the measures of effectiveness for evaluating the performance of the selected work zone control strategies and comparing them to the traffic control used by NDOR. The data were also used for the calibration and validation of the WZSIM computer simulation model developed by the University of Nebraska-Lincoln and described in Chapter 4.

TABLE 5-1 Field Data Collected.

Measure of Effectiveness	Data Type	Location	Data Collection Method
Capacity	Volume	Merge area	Traffic count data from Autoscope analysis of video tapes.
Lane Distribution	Traffic Counts	Merge area and several points upstream	Traffic counting manually and using the Autoscope
Speed Distribution	Speed	Merge area and several points upstream	Speed data from Autoscope analysis of video tapes, Laser gun
Traffic conflicts	Erratic Maneuvers	Merge area	Determined visually from video tapes

DATA COLLECTION

As during the preliminary study, traffic data were collected using the VDAS and two camcorders according to the procedure described in Chapter 2. To provide a field of view which makes automated data reduction possible, the cameras were set-up close to the roadway (*i.e.*, only a few feet away from the shoulder) and elevated to heights of at least 16 feet above the elevation of the roadway. One of the mobile video recording platforms was always located behind the taper at the lane closure. To observe the development of queues in periods of congested flow, the traffic upstream of the lane closure was recorded from overpasses or other vantage points on the roadside.

The camcorders and VDAS were occasionally relocated during the field studies to obtain data over the entire length of the approach to the lane closure.

At locations where video recording was not possible, speed data were collected using laser guns, while traffic flow and lane distribution were determined by manual counting.

LATE MERGE

The Late Merge traffic control plan was studied at a work zone on northbound I-79 north of Canonsburg, Pennsylvania. The traffic control plan is shown in Figure 5-1. The left lane of the two northbound lanes was closed. As described in Chapter 3, the Late Merge primarily differs from other traffic control plans in that it encourages drivers to use either lane until they reach the designated merge point. This type of traffic control was accomplished by placing the signs "USE BOTH LANES TO MERGE POINT" and "MERGE HERE TAKE YOUR TURN" on both sides of the roadway. The locations of these signs are shown in Figure 5-1. The two signs are shown in Figures 5-2 and 5-3.

Data Collection

Traffic data were collected on four days mainly during high-flow periods. Both uncongested and congested flow conditions were studied. Videotape recordings were made from various points in advance of the work zone, and speed data were collected using laser guns.

The most critical roadway section is between the merge point and the tapered section in advance of the work zone. Therefore, a VDAS video recording platform was setup on the shoulder behind the taper. The camera on the platform was elevated to a height of 30 feet, and focused on the merging operation of vehicles in this zone. Traffic volume, lane distribution, speed and density were recorded. In addition, driver behavior and traffic conflicts were also observed. About 18 hours of traffic flow were recorded at the taper during the period of the field study.

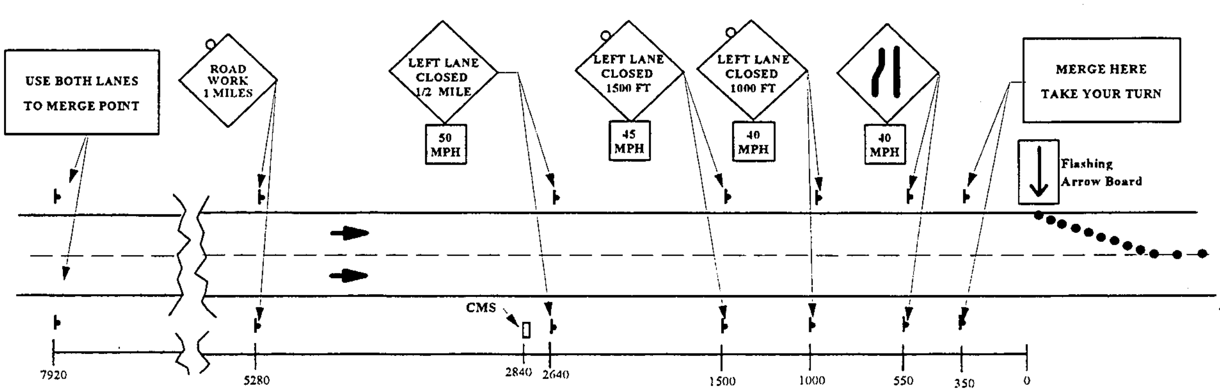


FIGURE 5-1 Late Merge Study Site.

FIGURE 5-2 "USE BOTH LANES TO MERGE POINT" Sign.

FIGURE 5-3 "MERGE HERE TAKE YOUR TURN" Sign.

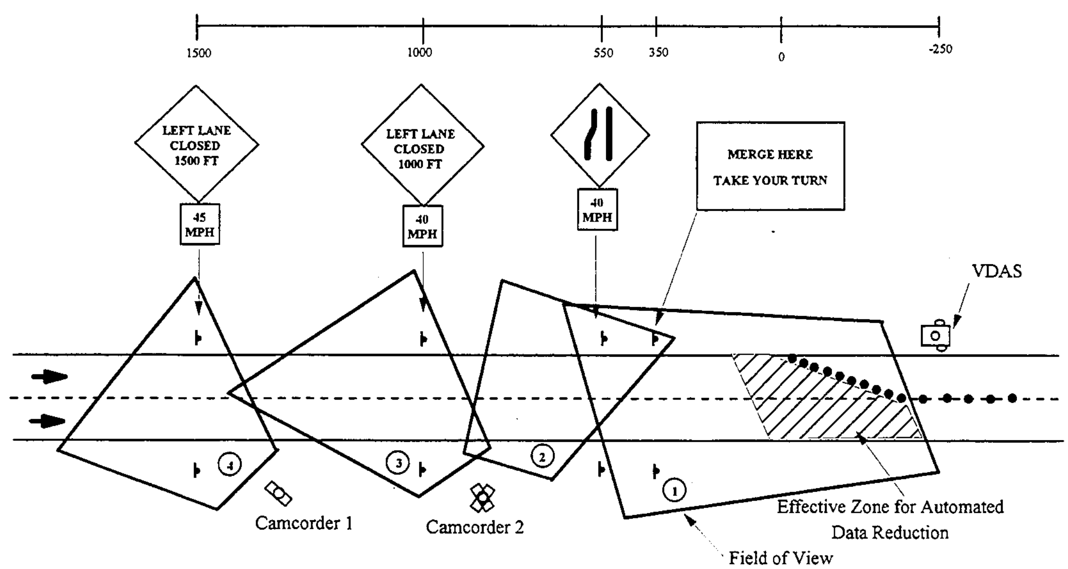


FIGURE 5-4 Camera Fields of View for Late Merge Field Study.

Figure 5-4 shows the area of the work zone approach covered by the camera's field of view. The camera was directed so that speed, traffic flow and time headway measurements were possible on a roadway section of approximately 300 feet.

Lane distribution and driver behavior could have been monitored for a length of approximately 1,500 feet in advance of the tapered section. This was accomplished using two camcorders. Camcorder recordings were made from three vantage points on the roadside, approximately 60 feet above the roadway. The camcorders were occasionally relocated during the field study to obtain data all along the approach to the lane closure. Figure 5-5 shows the location of the video recording platform and one of the camcorders.

Analysis of Data

Lane Distribution

Lane distributions were observed at seven points in advance of the work zone for both congested and uncongested flow conditions. The seven observation points were: (1) at beginning of the taper (0 feet); (2) the merge symbol sign (550 feet); (3)-(5) the LEFT LANE CLOSED signs at 1,000 feet, 1,500 feet and ½ mile in advance of the lane closure; (6) the USE BOTH LANES TO MERGE POINT (7,920 feet); and (7) at a point at 13,200 feet in advance of the lane closure. To account for the differences in the behavior of truck and passenger car drivers as they approach a lane closure, the lane distribution was determined for each vehicle type. The lane distributions are shown in Figure 5-6.

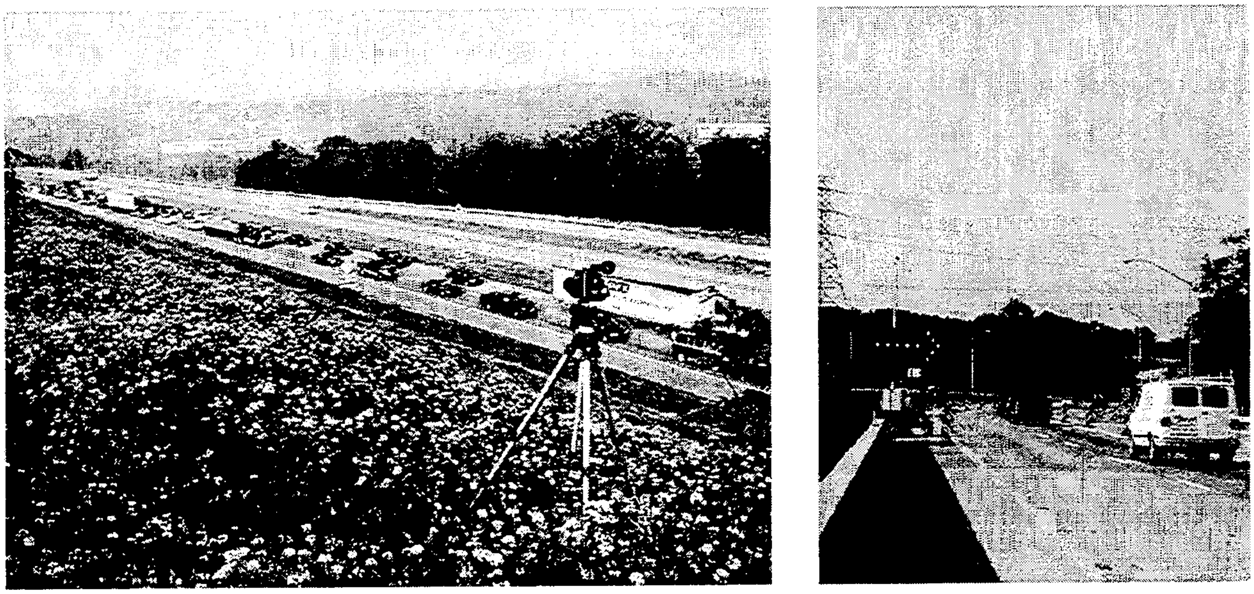


FIGURE 5-5 Camera Locations for Late Merge Field Study.

The lane distributions indicate that both passenger cars and trucks move to the open lane after passing the USE BOTH LANES TO MERGE POINT sign instead of remaining in the closed lane until they reach the merge point. However, higher percentages of passenger cars remained in the closed lane under congested flow conditions, which indicates that they are more likely to comply with the Late Merge when congestion develops. Trucks were also more likely to remain in the closed lane under congested flow conditions until they reached the LEFT LANE CLOSED 1500 FT sign, which is indicative of the greater degree of difficulty truck drivers have in merging from left to right. As described by the truck drivers, who participated in the brainstorming session, see Chapter 2, it is easier for them to merge from the right to left because they have a better view of traffic approaching from behind when it is on their left side. Therefore, one would expect fewer trucks to have remained in the closed (left) lane at this study site.

Although generally a higher percentage of the cars than trucks used the left lane, the lane distribution curves of the two vehicle types show similar tendencies in advance of the LEFT LANE CLOSED ½ MILE sign. However, beyond this point there was a significant difference between cars and trucks in terms of their lane preference under congested flow conditions. Truck drivers tried to move to the right (open) lane as soon as possible, and generally about 95 percent of them were already in the right lane at the LEFT LANE CLOSED 1500 FT sign. On the other hand, about 30 percent of the cars stayed in the left (closed) lane until the LEFT LANE CLOSED 1000 FT sign, where the symbolic left lane reduction transition sign and the MERGE HERE TAKE YOUR TURN sign (merge point) could first be seen. After passing this point, approximately 12 percent of the cars moved to the open lane before the merge point, and about 16 percent of them did so between the merge point and the taper.

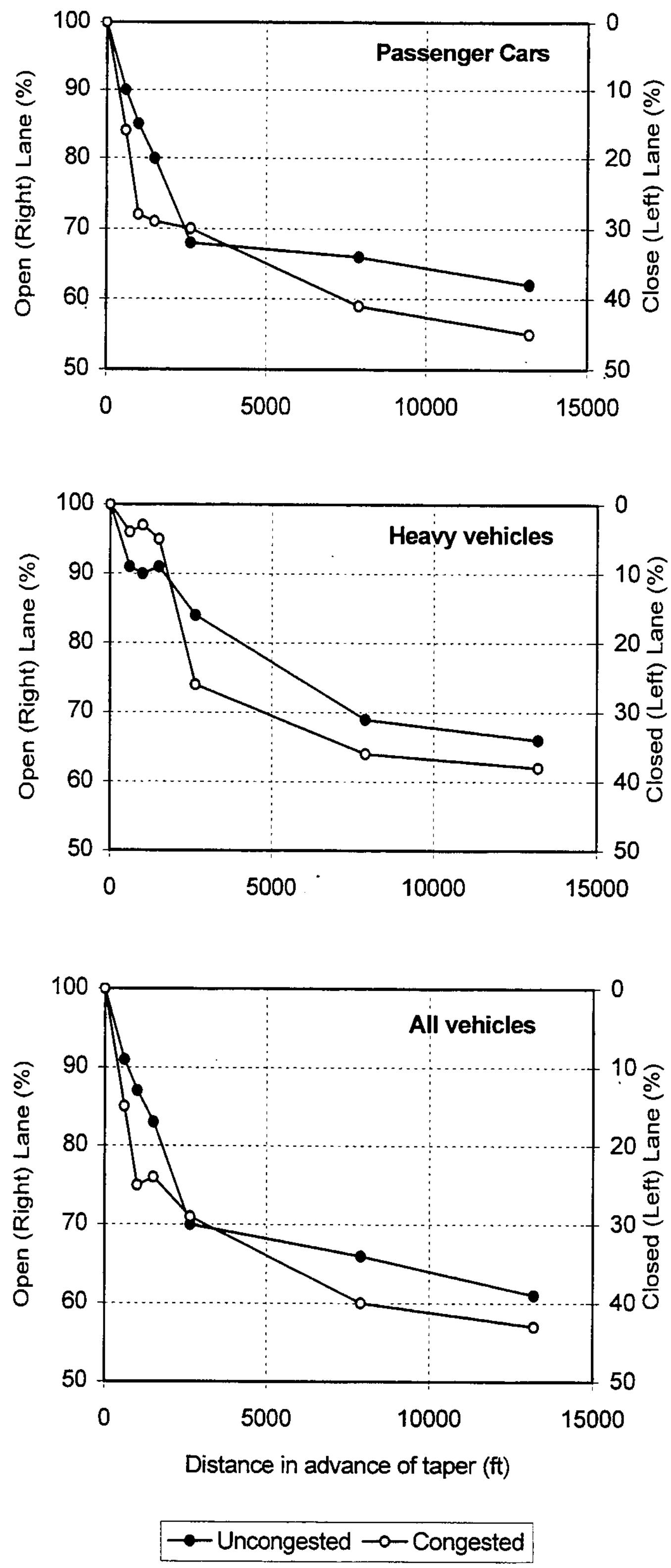


FIGURE 5-6 Lane Distribution for Late Merge.

Speed

Speed data were collected at the taper and three other locations upstream of the merge point under various traffic flow conditions. The image analysis of the video tapes recorded at the taper provided over 15,000 data points for passenger cars and over 2,500 for heavy vehicles. Laser guns were used to collect speed data at the other three locations. Samples of over 200 measurements were taken for each lane at every location.

A statistical analysis of the data was performed, and basic statistical parameters and frequency histograms were calculated. It was found that the speed data at each location were normally distributed. Figure 5-7 shows the frequency histograms and the fitted normal probability density functions for the speeds observed at the taper under uncongested and congested flow conditions. Both the Kolmogorov-Smirnov and the Chi-square goodness of fit tests, conducted at a significance level of 0.01, confirmed that the fitted normal distributions with the parameters given in Figure 5-7 are good approximations of the data set. As expected, the mean speed under congested flow conditions was significantly lower than under uncongested flow conditions.

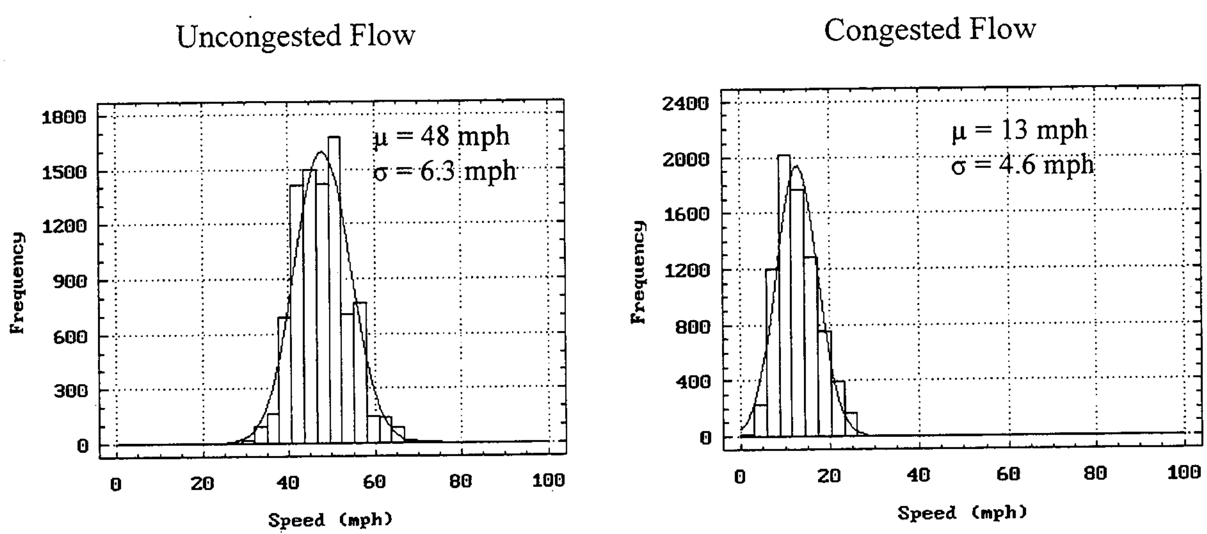


FIGURE 5-7 Speed Distributions for Late Merge.

Four speed profiles are shown in Figure 5-8. The profiles illustrate the variation of the mean uncongested flow speeds of passenger cars and heavy vehicles in the right and left lanes as they approach the lane closure. The posted and advisory speed limits are also indicated. As expected, the mean speed in the left lane are higher than in the right lane, and vehicles reduce their speed with an increasing rate as they get closer to the lane closure. The mean speeds of both cars and trucks were above the advisory speed limit at nearly every point, and they also exceeded the posted speed limit of 55 mph until the point of the first advisory speed sign of 50 mph.

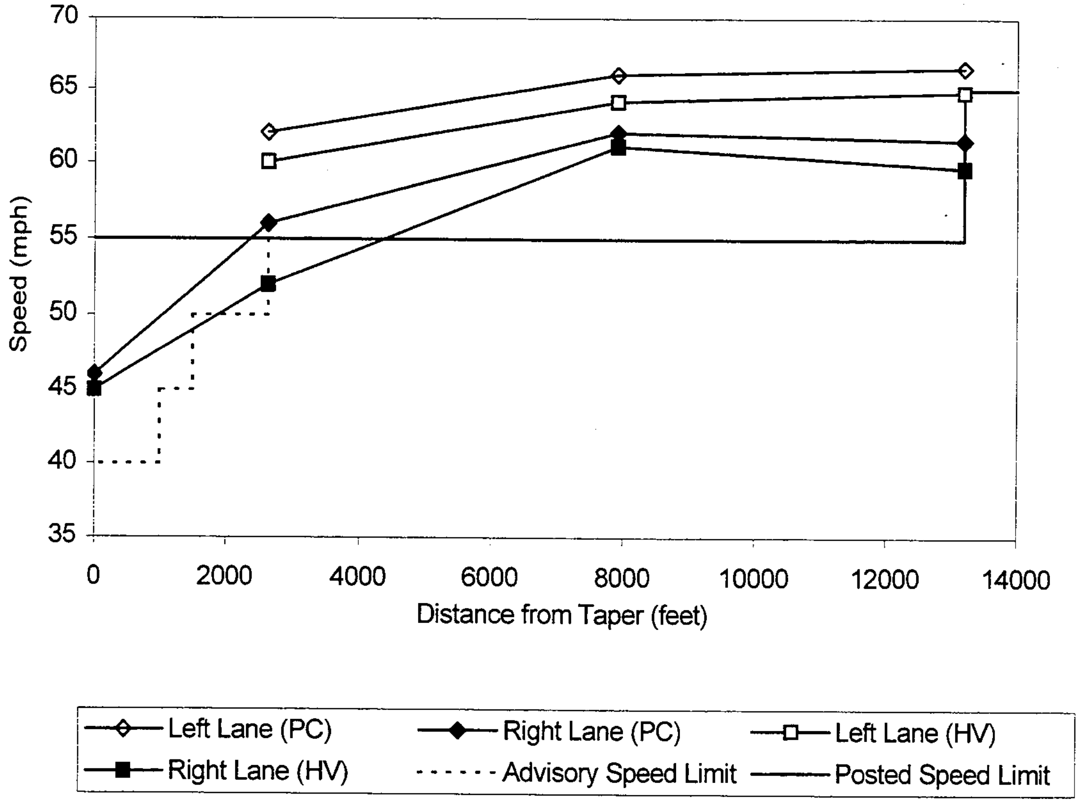


FIGURE 5-8 Speed Profiles for Late Merge.

Work Zone Capacity

To estimate the capacity of the work zone, speed-flow-density relationships were determined (*5, 20*). The speed-flow-density relationships observed during the field study are shown in Figure 5-9. The data points corresponding to uncongested conditions are marked by triangles and those points which represent congested flow conditions are indicated as circles. A piecewise linear model (*20*), was fitted to the data points. Each two-segment curve in Figure 5-9 has a discontinuity, and the speed-volume relationship has two peaks. The segment of low density corresponds to uncongested flow, and the segment of high density to congested flow. The peak on the low density portion of the curve is 1,470 vph, while the peak on the high density portion of the curve is less than 1,150 vph. Based on Edie's theory (*20*) these are the two capacity values for the work zone depending on whether the capacity is approached from stable flow (*i.e.*, a stable, moving traffic stream) or forced flow. In other words, the capacity of the control strategy would be 1,470 vph under uncongested flow conditions. But, once demand exceeds 1,470 vph, the congested flow capacity would be 1,150 vph.

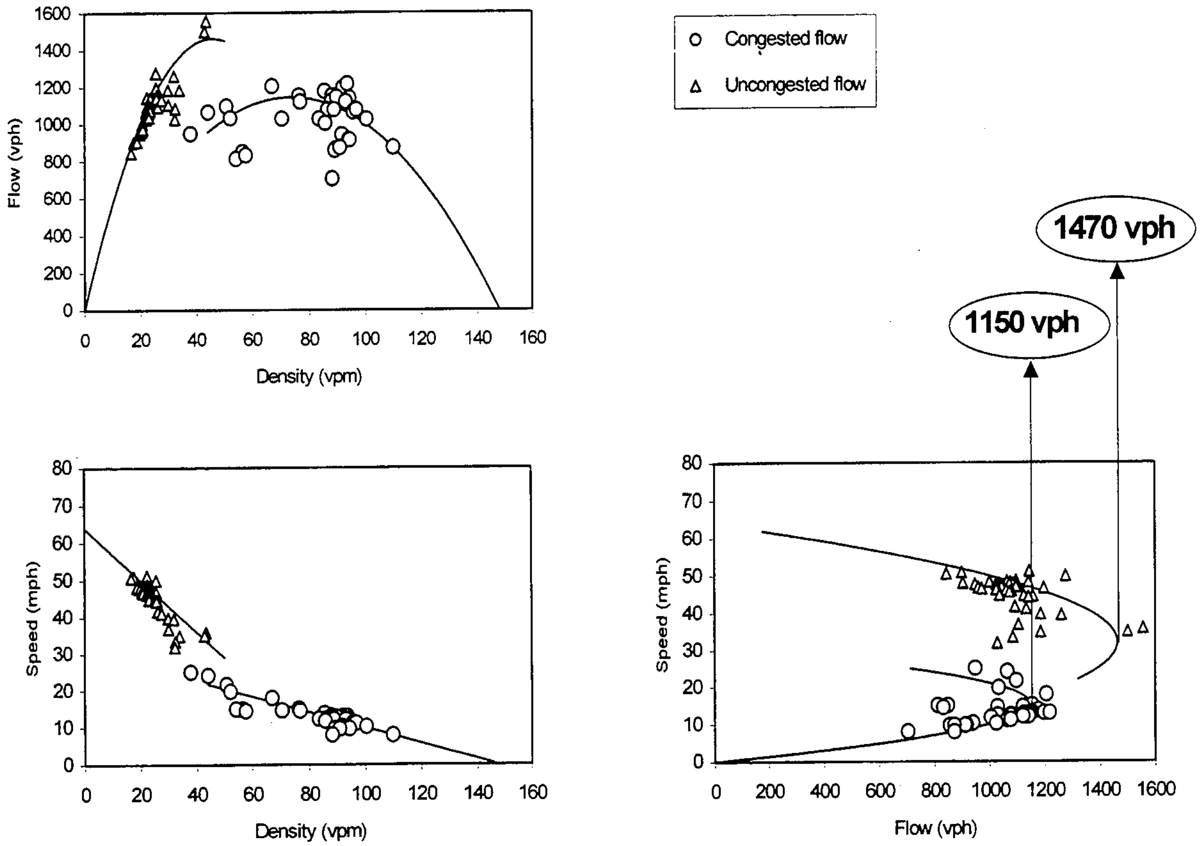


FIGURE 5-9 Speed-Flow-Density Relationships for Late Merge

The congested periods can be easily identified on the time series of observed speed and traffic volume data plotted in Figure 5-10. The data are for 15-minute periods and were obtained from the video tapes recorded at the taper. Each speed data point is an average value of the speeds of all vehicles observed during the 15-minute periods. Congested flow periods are indicated by the shaded time intervals. The first and longer congestion occurred between 6:15 and 8:45 am, and another shorter period of congestion occurred between 5:00 and 6:00 pm. These periods were verified visually by reviewing the video tapes. A sharp decrease of the speed can be observed during both congested periods coinciding with volumes persistently exceeding 1,400 or 1,500 vph, suggesting a capacity of approximately 1,450 vph.

Traffic Conflicts

Traffic conflicts may be used as measures of the safety effectiveness of a work zone traffic control strategy. They make it possible to compare alternative work zone control strategies on a safety basis. The video tapes recorded during the field study were reviewed to identify traffic conflicts associated with the merging operations in advance of the lane closure. Three main types of conflicts were observed:

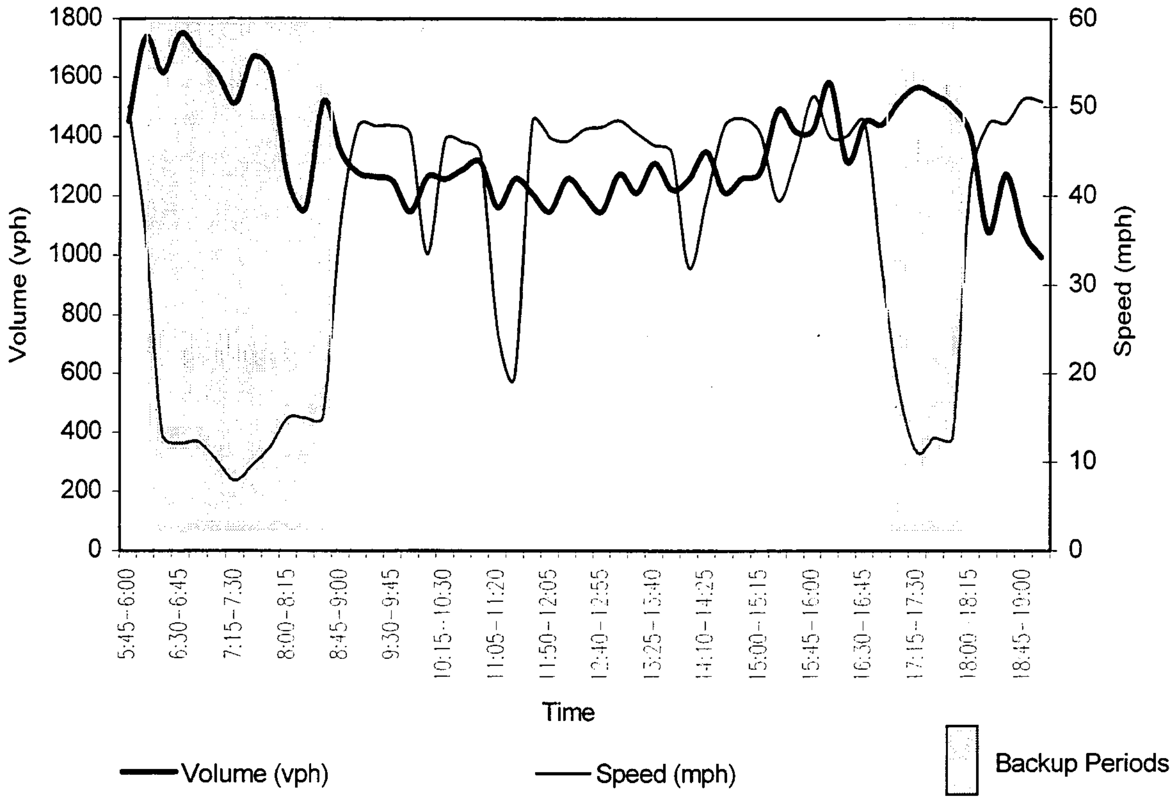


FIGURE 5-10 Traffic Flow and Speed Time Series for Late Merge.

1. *Forced merges*: a vehicle in the closed lane attempted to merge into the open lane when the available gap was not sufficient for performing a safe lane changing maneuver. It then led to evasive actions that had to be taken by either the merging vehicle or the vehicles in the open lane to avoid collision.

2. *Lane straddles*: a vehicle straddled the centerline of the roadway occupying both lanes to prevent other vehicles from passing it in the merge area.

3. *Lane blocking*: two vehicles, typically trucks, moving slowly, traveling side-by-side, blocking both lanes, and preventing other vehicles from passing them in the open lane.

The number of traffic conflicts and the traffic volumes were noted for each hour of video tape recorded at the taper. About 60 percent of the conflicts were forced merges. Conflict-volume, conflict-speed, and conflict-density relationships were developed by simple linear regression analyses. The conflict-density relationships shown in Figure 5-11 were found to be the most robust with R^2 values between 0.79 and 0.90.

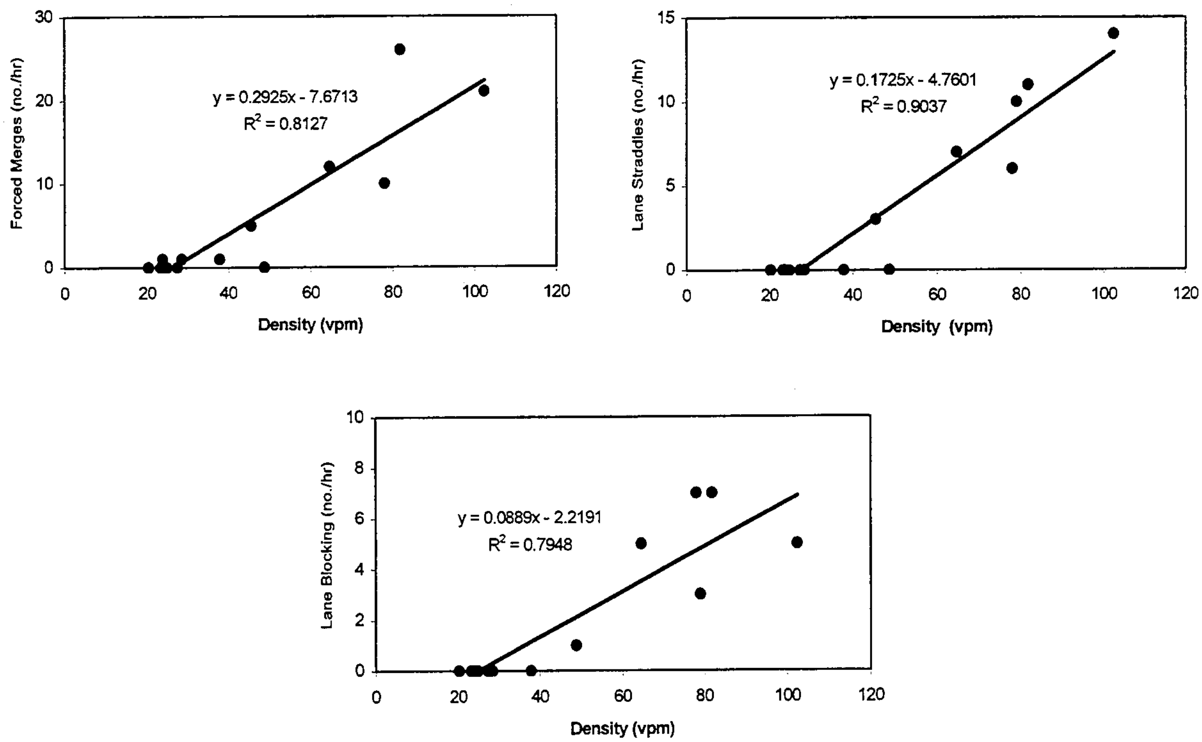


FIGURE 5-11 Traffic Conflicts for Late Merge.

As expected, each traffic conflict increased with density. Forced merges were the most sensitive to density variation. It increased with density at about twice the rate of lane straddles and four times the rate of lane blocking. The relationships indicate that none of the conflicts typically occur at densities below approximately 20 vpm. Thus, it can be expected that at an average speed of 50 mph none of these three traffic conflicts will occur if the volume does not exceed 1,000 vph.

Driver Survey

A survey was conducted to assess the opinions of drivers regarding the applicability of the Late Merge for improving traffic operations in advance of single lane closures on interstate highways.

The survey was conducted in a rest area which was located within the work zone, about 1.5 miles downstream from the merge point. Drivers who stopped at the rest area were asked to participate in the survey. A total of 88 interviews were completed during 16 hours. It was not possible to achieve a larger sample size during this period, because drivers were often not willing to be interviewed, especially during peak periods. Also, during the off-peak periods, when drivers were more willing to be interviewed, the number of drivers available was low.

The sample included 58 drivers of cars (*i.e.*, passenger cars, vans, pickups, or sport/utility vehicles) and 30 drivers of trucks (*i.e.*, single unit or tractor-trailer trucks). Most of the drivers were males (78 percent of the car drivers and all of the truck drivers). Also, most (72 percent) of the car drivers were from Pennsylvania or the neighboring states of Ohio and West Virginia, as were most (55 percent) of the truck drivers. The average driving experience was 27 years (31 years for car drivers and 20 years for truck drivers).

The drivers interviewed were asked a series of questions about any problems that they may have experienced with the Late Merge, their awareness of the Late Merge signing, their opinions regarding the effectiveness of the Late Merge, common problems they experienced in advance of lane closures at work zones on interstate highways, and their suggestions for improving traffic operations at these locations. The following is a summary of their responses to these questions.

The results of the survey indicate that the concept is not well-accepted by all drivers, especially truck drivers. The major problem experienced or observed by truck drivers was cars in the closed lane passing and merging ahead of them at the merge point. Even though the Late Merge permits this maneuver, it was viewed by many truck drivers as being unacceptable; the same as it would be in the case of the typical merge control used by NDOR for lane closures at interstate work zones. Also, many of the truck drivers did not believe that having a single merging point was a good idea because they thought that it actually increased congestion.

Car drivers were much more supportive of the Late Merge concept. They experienced or observed few problems with it, and they seemed to appreciate being able to use the closed lane to pass slower moving vehicles in advance of the merge point. Car drivers also liked the fact that they did not have to worry about changing lanes prior to the merge point.

Truck drivers viewed the behavior of car drivers as the most serious problem they encountered in advance of lane closures at work zones on interstate highways. Especially troublesome are those who speed by in the closed lane and merge into the open lane ahead of them. They suggested more law enforcement is needed to deter this behavior, as 13 percent of the car drivers did. Their concern about this problem may account, at least in part, for the failure of most truck drivers to believe that the Late Merge improves traffic flow, since it permits drivers to travel in the closed lane up to the merge point.

The results of the survey indicate that the potential benefits of the Late Merge will not be fully realized unless drivers, particularly truck drivers, have a better understanding and acceptance of the concept. It seems that many drivers are behaving and expect other drivers to behave in the same manner as they do in the case of conventional merge control in advance of lane closures (*i.e.*, merge as soon as possible into the open lane and do not use the closed lane to pass and merge ahead of slower vehicles, especially trucks). The fact that the USE BOTH LANES TO MERGE POINT signs were followed by a series of LEFT LANE CLOSED signs may have contributed to this behavior.

The sample size and scope of this survey were limited. Therefore, further research is needed to determine more clearly the extent of drivers' understanding and acceptance of the Late Merge concept in order to develop traffic control plans for the Late Merge that will maximize its effectiveness.

INDIANA LANE MERGE

The Indiana Lane Merge was studied at a work zone on southbound I-65 approximately 70 miles south of Chicago, near Remington, Indiana. The right lane of the two, southbound lanes was closed. The traffic control plan at the study site is shown in Figure 5-12. In contrast to the Late Merge, the Indiana Lane Merge traffic control plan encourages drivers to move to the open lane as early as possible in advance of the lane closure. It is achieved by establishing a dynamic NO PASSING zone which is activated during congestion, as described in Chapter 2. One of the DO NOT PASS WHEN FLASHING signs, equipped with an acoustic traffic sensor, is shown in Figure 5-13.

Data Collection

Traffic data were collected on four days during periods of uncongested flow. Congested flow conditions did not occur at any time during the four days. Videotape recordings were made from various points in advance of the work zone, and speed data were collected using laser guns. The VDAS video recording platform with the camera elevated to a height of 30 feet was setup on the shoulder behind the taper. It was used to study the traffic flow in the merge area in advance of the taper. In addition to collecting traffic volumes and speeds, traffic conflicts were also observed in the merge area. About 16 hours of traffic flow were recorded at the taper. Lane distribution and driver behavior were also monitored from this camera location on a length of approximately 1,500 feet in advance of the tapered section. Traffic flow upstream of the lane closure was recorded using two camcorders. They were stationed on a bridge located about 1.7 miles in advance of the lane closure, just upstream of the first DO NOT PASS WHEN FLASHING sign. One of the camcorders was used to record the traffic in both lanes at the location of this sign. Speed, traffic flow and time headway were determined from the video tapes recorded at this location. The other camcorder was focused on the traffic approximately half-way between the bridge and the lane closure. Automated data reduction of these video recordings was not possible because of the viewing angle. They were used to observe lane distributions. Figure 5-14 shows the location of the video recording platform and the camcorders.

Analysis of Data

Lane Distribution

Lane distributions for passenger cars and trucks were determined using traffic counts taken at five locations in advance of the work zone. Since congestion was not observed during the entire period of the field study, the lane distributions were for uncongested conditions only. Figure 5-15 shows the lane distribution of the different vehicle types as a function of their distance in advance of the lane closure. The data points from left to right represent the lane distributions at the four measurement locations: at the beginning of the taper (0 feet); the first stationary DO NOT PASS sign in advance of the taper (500 feet); the second dynamic DO NOT PASS WHEN FLASHING sign (3,450 feet); the fourth dynamic DO NOT PASS WHEN FLASHING sign (6,900 feet); and at the bridge where the camcorders were located (9,190 ft).

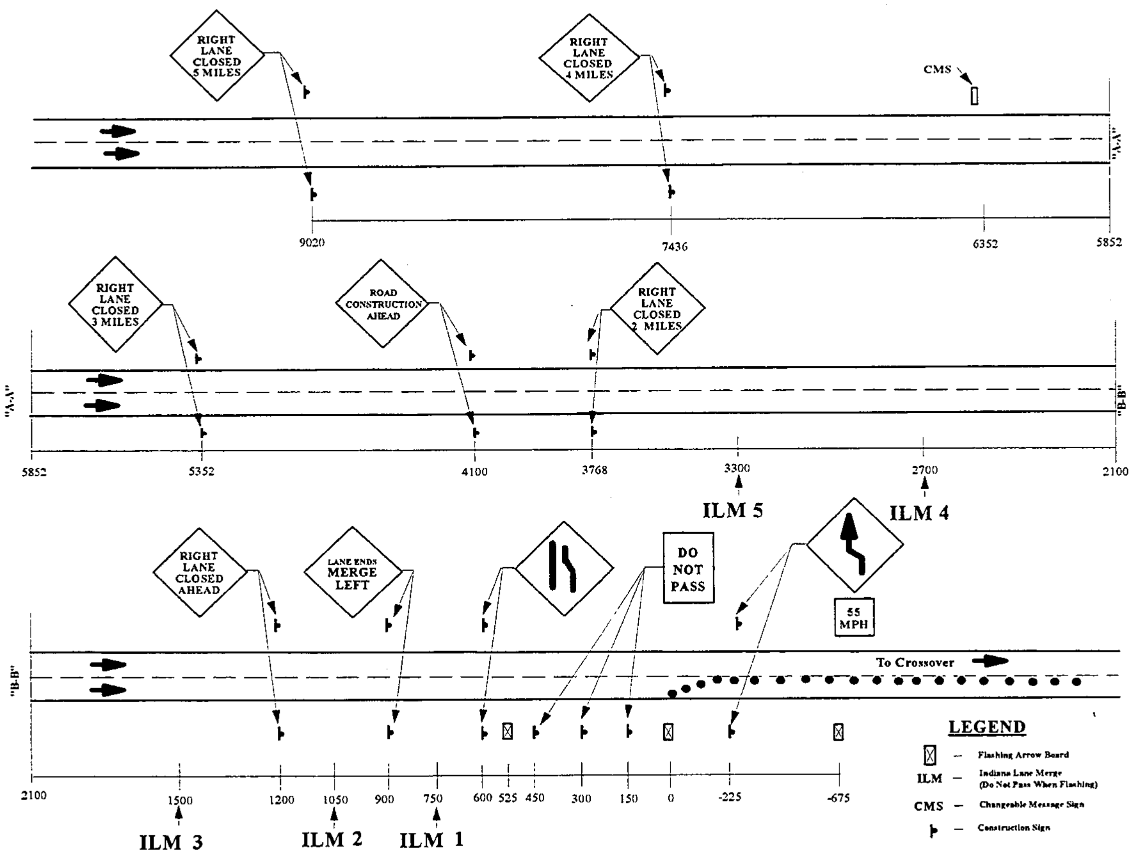
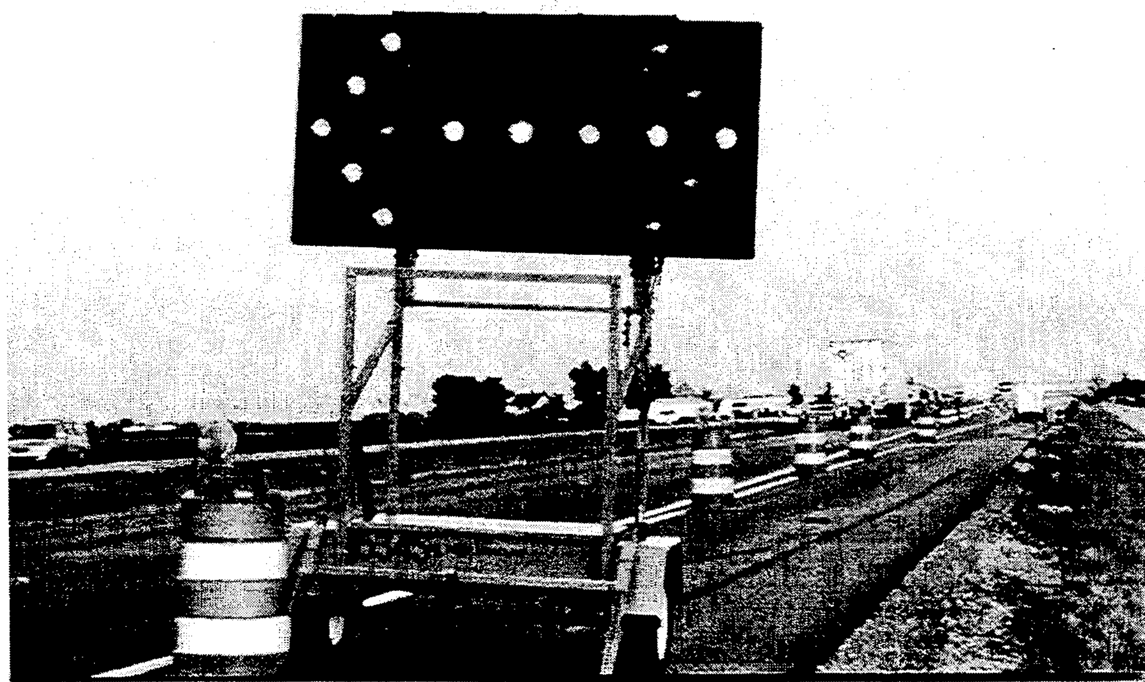


FIGURE 5-12 Indiana Lane Merge Study Site.

FIGURE 5-13 "DO NOT PASS WHEN FLASHING" Sign.



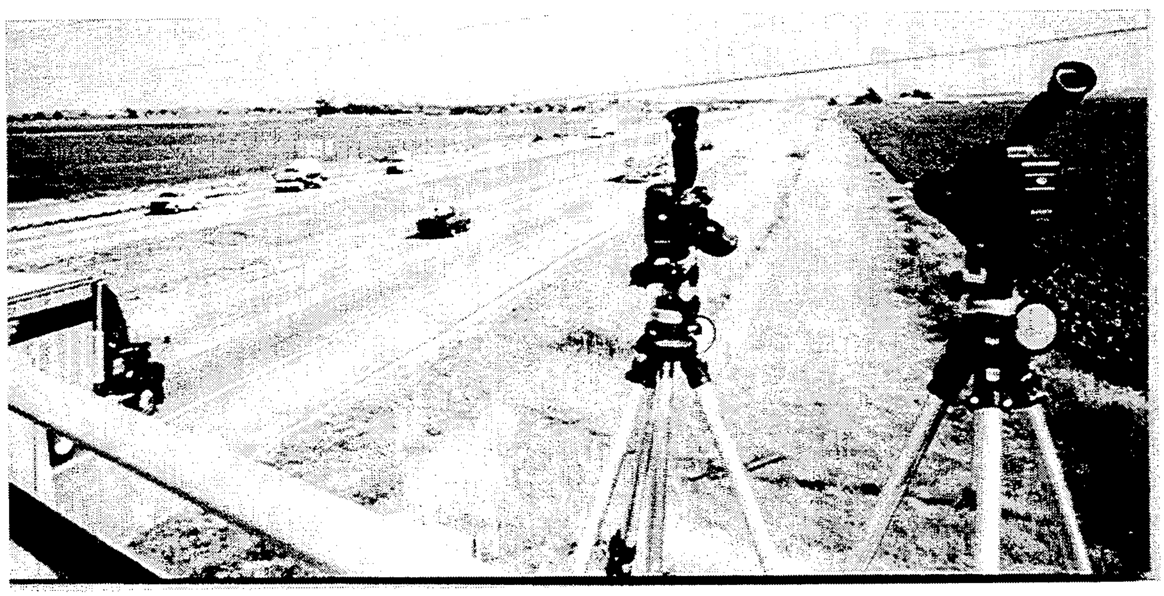


FIGURE 5-14 Camera Locations for Indiana Lane Merge Field Study.

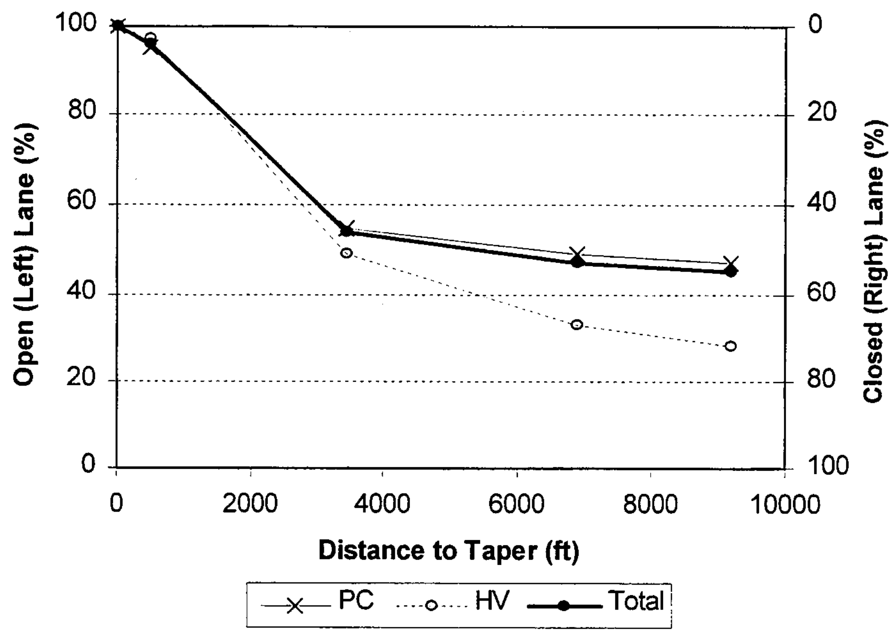


FIGURE 5-15 Lane Distribution for Indiana Lane Merge.

Since warning signs of the Indiana Lane Merge inform motorists about the lane closure as far as five miles in advance of the lane closure, they may have moved to the open lane sooner than they normally would have. At a distance of 9,190 feet in advance of the lane closure, 45 percent of the traffic was in the left (open) lane, and 55 percent in the right (closed) lane. Beyond this point to the location of the DO NOT PASS sign, vehicles were moving to the open lane with a steadily increasing rate. At a distance of 3,500 feet, 55 percent was in the open lane; and at 500 feet, 96 percent of the traffic was in the open lane. As expected, an initially higher percentage of cars used the left lane. However, trucks began to move sooner to the open (left) lane than cars; and at a distance of about 2,500 feet in advance of the lane closure, the lane distributions of the two vehicle types were about the same.

Speed

Speed data were collected at the taper and three other locations upstream from the merge point. The analysis of the video tapes recorded at the taper provided over 8,500 data points for passenger cars and over 1,300 for heavy vehicles. Laser guns were used to collect speed data at the other three locations.

A statistical analysis of the data was performed, and basic statistical parameters and frequency histograms were calculated. Figure 5-16 shows the frequency histogram and the fitted normal probability density function for the speeds observed at the taper under uncongested conditions. Both the Kolmogorov-Smirnov and the Chi-square goodness of fit tests, conducted at a significance level of 0.01, confirmed that the fitted normal distribution with the parameters shown in Figure 5-16 are good approximations of the data set. The relatively high standard deviation of speeds can be partly explained by the wide range of traffic volumes observed during the field study.

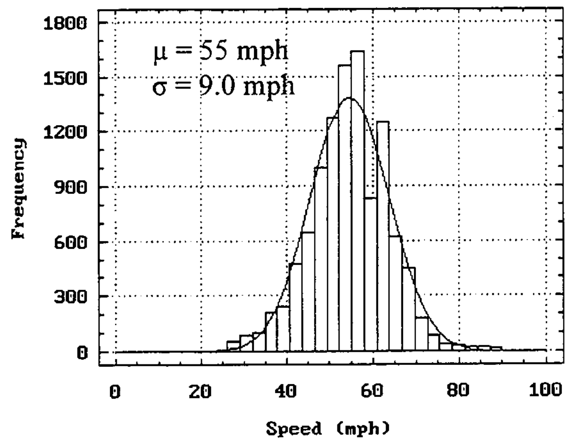


FIGURE 5-16 Speed Distribution for Indiana Lane Merge.

Work Zone Capacity

Speed-flow-density relationships were determined using data averaged over 15-minute periods. The data points shown in Figure 5-17 indicate that only uncongested flow conditions were observed during the field study. Therefore, fitting any type of relationship to these data points would not provide an estimate of the capacity of the work zone. However, it is apparent from the data that the capacity is higher than 1,300 vph.

According to a modeling study of the Indiana Lane Merge system conducted by the Purdue University, the work zone capacity can be estimated as 1,430 vph. Similar values were observed at other Indiana locations (*21*). Therefore, this value was used in comparing the Indiana Lane Merge to the Late Merge and NDOR Merge.

Traffic Conflicts

The video tapes recorded at the taper were reviewed to determine the frequency of traffic conflicts associated with the merging operations in advance of the lane closure. However, after reviewing 16 hours of tape, only seven conflicts (four forced merges and three lane straddles) were observed. This may be indicative of the safety effect of the Indiana Lane Merge. But, it is also likely that it may be a consequence of the lack of congestion during the period of the field study. Further investigation of the traffic control plan is needed to determine whether the dynamic no-passing zone would significantly reduce the merge-related traffic conflicts during congested periods, or if it would just simply shift their location upstream when a passing zone is activated by the queue.

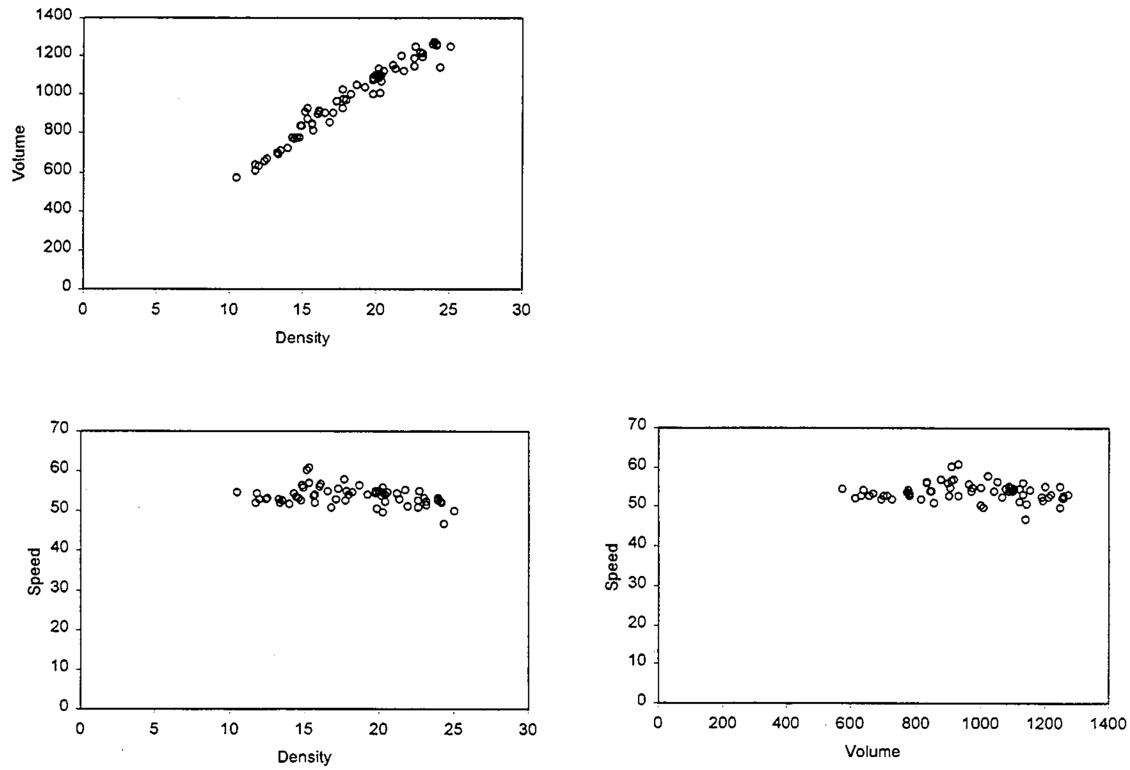


FIGURE 5-17 Speed-Flow-Density Relationships for Indiana Lane Merge.

Driver Survey

A survey was conducted to assess the drivers opinion on the effectiveness of the Indiana Lane Merge. The survey was performed at a truck stop located at an interchange within the work zone. Because the survey site was a truck stop, almost 90 percent of the respondents were truck drivers. There were only 8 car drivers out of 74 total respondents. Therefore, the survey results do not adequately represent the opinion of car drivers.

The results indicated that trucks were often in the open lane prior to the lane closure notice, because they had received advance warning of the lane closure from other truck drivers via CB radio. Most car drivers do not have this advantage and are not warned of the lane closure until the signs notify them.

Unlike the results of the driver survey for the Late Merge, truck drivers interviewed in Indiana noted fewer merging troubles than car drivers did. However, about half of the truck drivers mentioned that cars racing ahead was the main reason for merging problems. On the other hand, car drivers said that vehicles in the open lane not allowing vehicles to merge from the closed lane was the main problem. As was found in the Late Merge survey, car drivers and truck drivers view the merging problem differently. Each often blaming the other for the ineffectiveness of work zone traffic control.

The majority of both car and truck drivers stated that the lack of traffic was the major contributing factor to not experiencing merging difficulty. This response was consistent with the relatively low volume of traffic observed during the field study, and may also explain why the drivers did not observe many merging difficulties when entering the work zone.

Interestingly, over half of the truck drivers did not believe that the Indiana Lane Merge improved traffic operations, and about one-third of them thought that it did improve traffic operations. Most of the truck drivers, who did not think it helped, said that cars ignored the DO NOT PASS signs. About half of those who found the signs useful said that the signs improved the work zone by causing vehicles to merge sooner. It was also mentioned that the signs stopped vehicles from racing ahead.

When asked about the most common problem in work zones, truck drivers again cited vehicles racing to the merge point as the number one problem. They also mentioned drivers merging too late, and not paying attention. Generally when the respondents were asked about how to improve work zones, most did not have any suggestions. Most of those who had a suggestion cited law enforcement as a solution to work zone problems.

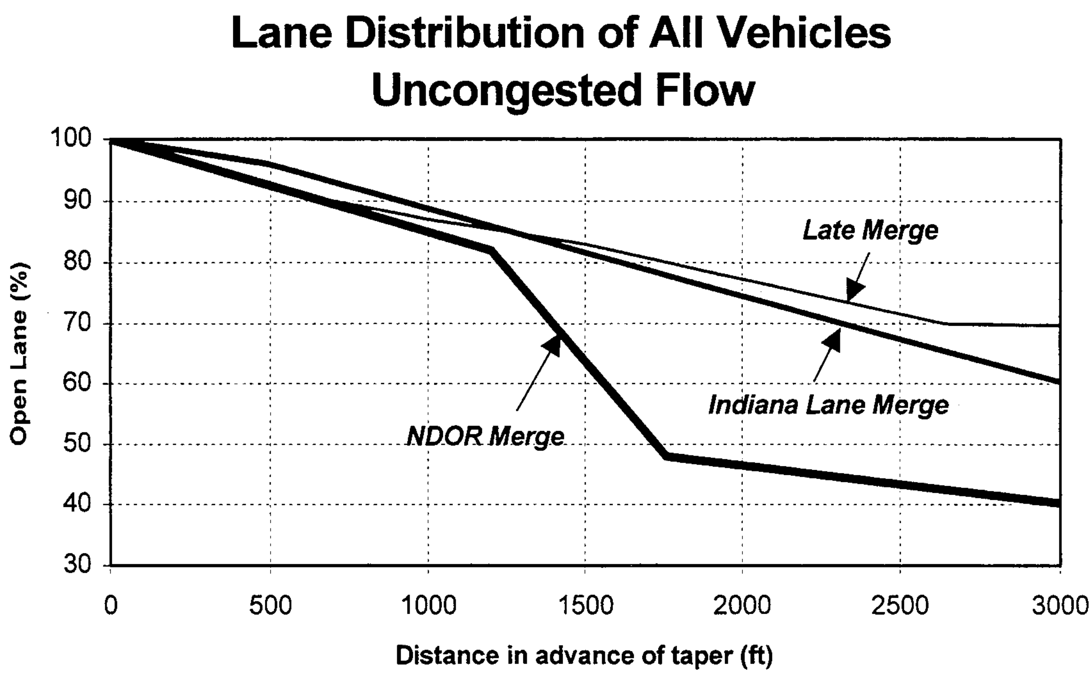
COMPARISON OF ALTERNATIVES

The results of the field studies of the Indiana Lane Merge and Late Merge were compared with those of the preliminary field studies of the NDOR Merge to evaluate their effectiveness in improving the safety and efficiency of merging operations in advance of lane closures. The alternatives were compared on the basis of the measures of effectiveness determined from the field studies (*i.e.*, lane distribution, capacity, speed distribution, and traffic conflicts). The results of the comparison are presented below.

Lane Distribution

The lane distribution of traffic approaching a lane closure is indicative of the effectiveness of merging operations (*2,3,4*). The two graphs in Figure 5-18 show the lane distributions of all vehicles within 3,000 feet in advance of the lane closures at the study sites in Nebraska, Pennsylvania, and Indiana. Before making any comparison, it is important to note that the right lane was closed in the cases of the NDOR Merge and the Indiana Lane Merge, whereas the left lane was closed in the case of the Late Merge.

Since the advance warning signs of the Indiana Lane Merge inform motorists about the lane closure farther in advance than those of the NDOR Merge, about 20 percent more vehicles were in the open lane at a distance of 3,000 ft to the lane closure. For the same reason, vehicles were moving to the open lane sooner than they did for the NDOR Merge. Also, the merging operations associated with the NDOR Merge were concentrated over a 500-feet section from 1,200 to 1,700 feet in advance of the lane closure; whereas merge operations with the Indiana Lane Merge occurred over



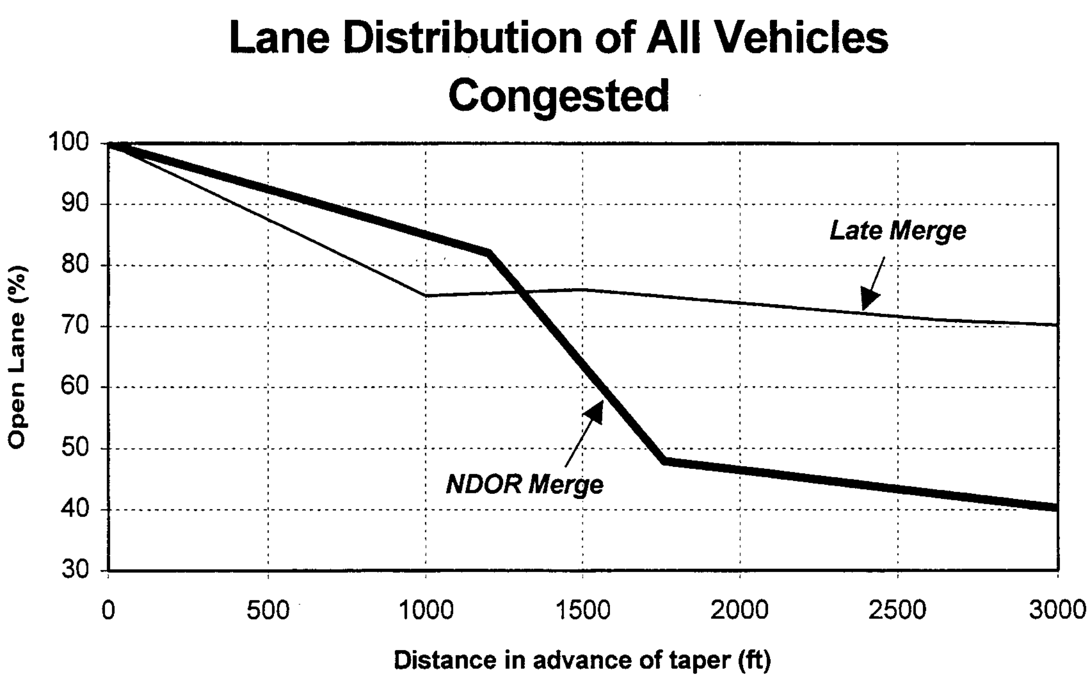


FIGURE 5-18 Comparison of Lane Distributions.

a much greater distance. The longer merging zone for the Indiana Lane Merge resulted in safer lane changing maneuvers as indicated by the very low number of traffic conflicts observed during the field study.

Normally vehicles travel in the right lane. Therefore, the comparison between the Late Merge and the other control strategies is confounded by the fact that it was used at a left-lane closure, and the other two were used at right-lane closures. If different lanes are closed, the comparison of lane distributions is not so obvious; and it makes more sense to compare the slopes of the lane distribution curves than the actual vehicle percentages. Figure 5-18 indicates that during uncongested flow, vehicles under the Late Merge control changed lane in a similar manner as those of other traffic control plans. However, during congested periods, their behavior was more consistent with the Late Merge concept (*i.e.*, they remained in the closed lane longer). It is expected that a more significant difference would be observed in the case of right-lane closures.

Capacity

The capacity values estimated for the three work zone control strategies were initially expressed in vehicles per hour. However, these values do not account for the differences in topography and truck percentages observed at the study sites. Therefore, the capacity values were adjusted using appropriate passenger car equivalents (PCE) to account for these effects. The PCE depends on both the topography (*i.e.*, magnitude and length of grade) and truck percentage. The PCE values used here were taken from the 1994 Highway Capacity Manual(*5*). Table 5-2 shows the capacities of the three alternatives in vehicles per hour (vph) and passenger cars per hour (pcph). The same PCE was used for the NDOR Merge and the Indiana Lane Merge because the observed truck percentages were about the same, and the grades were less than 2 percent at both locations. In Pennsylvania, the roadway in advance of the lane closure was on a 2-percent grade that was longer than 1.5 mile. Therefore, a higher PCE of 2.5 was used for the Late Merge. In terms of pcph, the observed work zone capacities of the Indiana Lane Merge and the Late Merge are about 5 and 18 percent higher than for the NDOR merge, respectively.

TABLE 5-2 Capacities of the Work Zone Control Alternatives.

Alternative	Observed			Capacity (pcph)
	Max Flow Rate (vph)	Percent Trucks	PCE [a]	
NDOR Merge	1,360	15	1.5	1,460
Indiana Lane Merge	1,430	16	1.5	1,540
Late Merge	1,470	12	2.5	1,730

[a] 1994 Highway Capacity Manual

Speed Distribution

The frequency histograms of the observed speeds for the three alternatives and the fitted normal probability density functions are shown in Figure 5-19. The speed distributions were determined for both uncongested and congested flow conditions. For the Indiana Lane Merge, only uncongested flow speeds were observed during the entire period of the field study. For the NDOR Merge, the speed distribution under uncongested flow conditions was determined from the data collected at the Gretna study site; whereas, the distribution for congested flow conditions was calculated from the Omaha data. However, it should be noted, that the speeds collected in Omaha were actually for near-congested flow conditions, because no sustained periods of congestion were observed at the Omaha study site.

As expected, the mean speed under congested flow conditions was lower than under uncongested flow conditions, especially in the case of the Late Merge for which sustained periods of congestion were observed during the field study. However, the standard deviations of the speed distributions for the Late Merge were smaller than those for the other two alternatives. The smaller speed variances are indicative of lower accident potential, and suggest that the Late Merge may provide safer traffic operations.

Traffic Conflicts

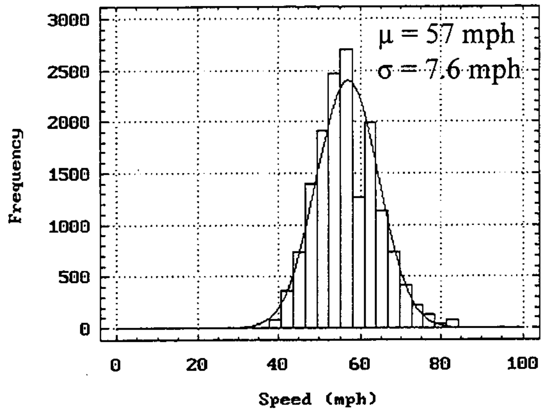
The Indiana Lane Merge was found to be the most effective in terms of traffic conflicts, because only seven conflicts were recorded in 16 hours of field study. However, these observations were only for uncongested flow conditions, since congested flow conditions never developed during the field studies of the Indiana Lane Merge. Therefore, more studies are needed to determine how the system would behave under congested flow conditions, before conclusions can be reached regarding its overall safety effects.

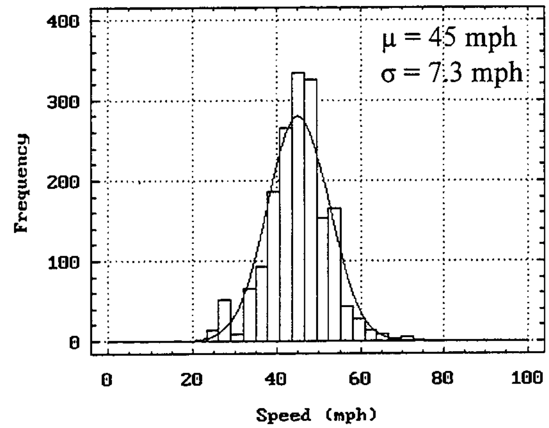
The comparisons of the traffic conflicts associated with the Late Merge and NDOR Merge are shown in Figure 5-20. Traffic conflicts were considerably lower using the Late Merge. At higher densities, the Late Merge have about 75 percent fewer forced merges and about 30 percent fewer lane straddles than the NDOR Merge. The improvement was even more significant at lower densities. Also, traffic conflicts were not observed at densities below 25 vpm with the Late Merge; whereas, they were observed at lower densities with the NDOR Merge.

Thus, the results of the traffic conflicts analysis suggest that both the Late Merge and the Indiana Lane Merge provide safer merging operations than the NDOR Merge. Although the Indiana Lane Merge was found to produce the fewest traffic conflicts, it can not be declared to be safer than the Late Merge, because it was not observed under congested flow conditions.

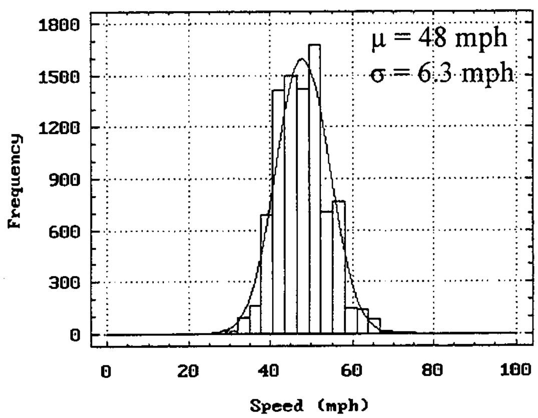
Uncongested Flow / Congested Flow

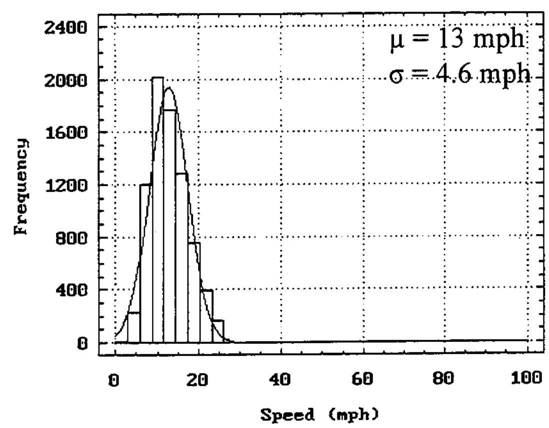
NDOR Merge





Late Merge





Indiana Lane Merge

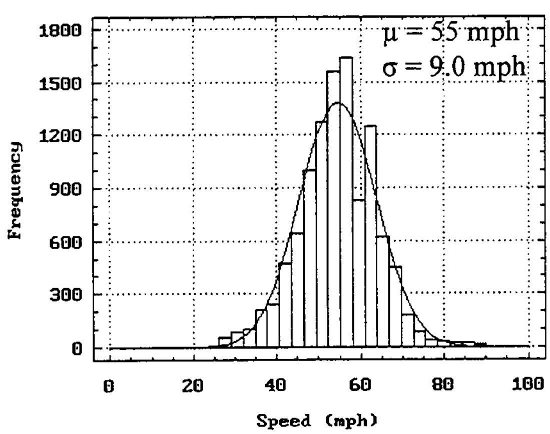


FIGURE 5-19 Comparison of Speed Distributions.

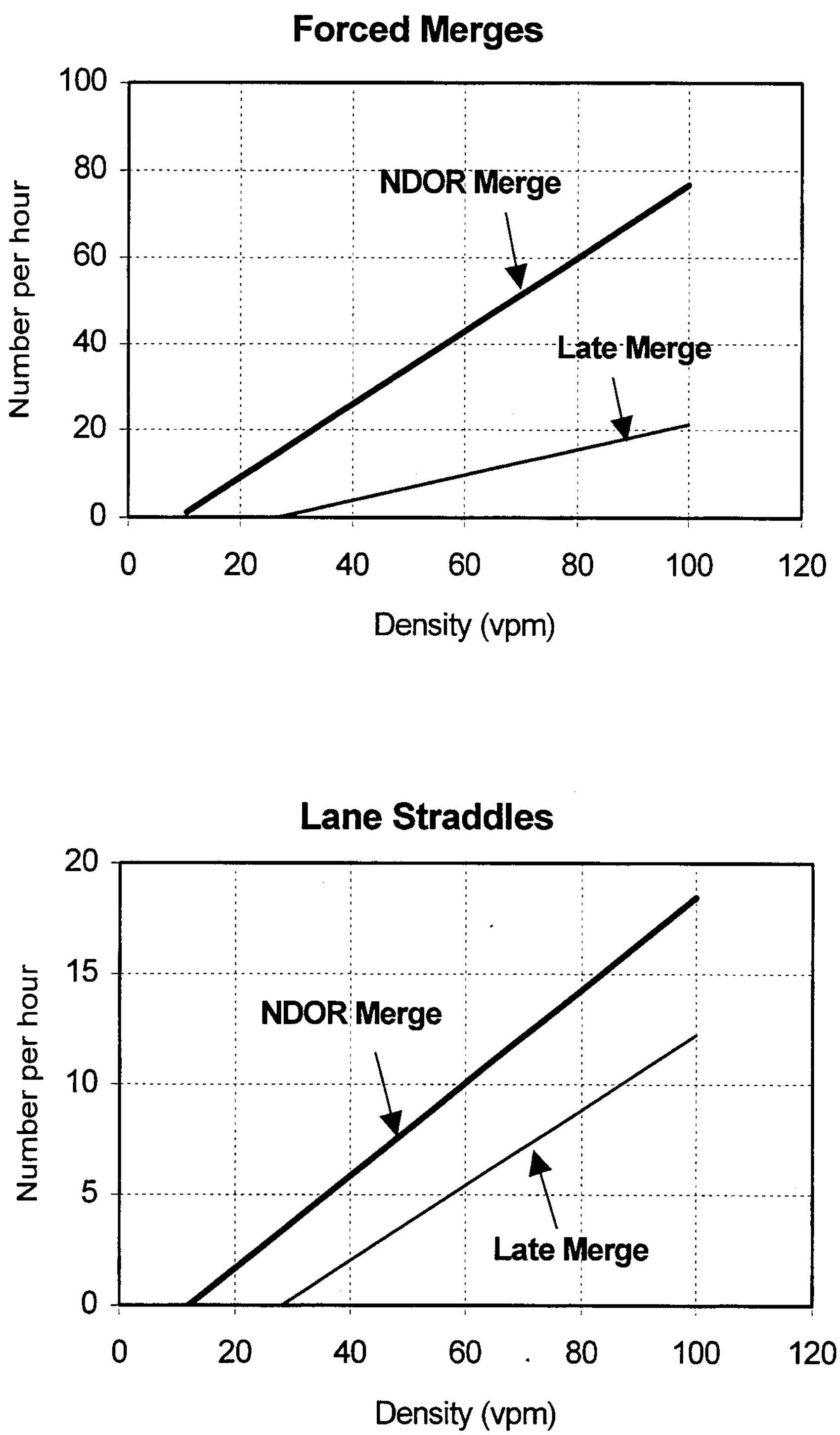


FIGURE 5-20 Comparison of Traffic Conflicts.

SUMMARY

The results of the field studies indicate that both the Indiana Lane Merge and Late Merge are more effective than the NDOR Merge in terms of the safety and efficiency of merging operations in advance of lane closures on interstate highways. Both alternatives have higher capacities than the NDOR Merge, which would reduce the frequency and severity of congestion associated with lane closures. According to the results of the field studies, the capacity of the NDOR Merge is 1,460 pcph; whereas, the capacities of the Indiana Lane Merge and Late Merge are 1,540 and 1,730 pcph, respectively.

Also, both the Indiana Lane Merge and the Late Merge produce fewer traffic conflicts associated with merging operations in advance of lane closures. Traffic conflicts rarely occurred with the Indiana Lane Merge under uncongested flow conditions, and traffic conflicts were much less frequent with the Late Merge than with the NDOR Merge under both uncongested and congested flow conditions.

The results of the driver surveys conducted at the Indiana Lane Merge and the Late Merge study sites indicate that some drivers, especially truck drivers, are skeptical of the effectiveness of these control strategies. In general, these drivers do not believe that other drivers comply with the DO NOT PASS signs of the Indiana Lane Merge. Many of them expressed the need for more law enforcement in order to improve traffic operations at work zones.

In the case of the Late Merge, some drivers, especially truck drivers, complained about vehicles passing them in the closed lane and merging into the open lane ahead of them at the merge point; a maneuver that is permitted by the Late Merge. This suggests that the signing used to effect the Late Merge was not adequate to restructure drivers' expectancies based on their prior experience at conventional lane closures. Many truck drivers also questioned the benefit of a single merge point, and seemed to believe that it actually increased congestion. This ambivalence expressed by truck drivers may have been associated with the greater difficulty they have merging from the left lane to the right lane, which was the case at this study site. Although these concerns may have been somewhat site specific, it is apparent that the potential benefits of the Late Merge will not be realized unless drivers, especially truck drivers, have a better understanding and acceptance of the concept.

Chapter 6

BENEFIT-COST ANALYSIS

The results of the field studies in Chapter 5 indicate that both the Indiana Lane Merge and Late Merge are more effective than the NDOR Merge, especially under high traffic volumes and during periods of congestion. They also suggest that the Late Merge would be more effective if its signing was more intelligible and responsive to traffic flow conditions. In addition, the results of the simulation analysis in Chapter 4 reveal that the "Smart" Work Zone has the potential to substantially improve the safety and efficiency of merging operations in advance of lane closures. However, each of these alternatives are more expensive to implement than the NDOR Merge. Therefore, a benefit-cost analysis was conducted to determine the cost-effectiveness of these alternatives and to identify the most cost-effective alternatives over a range of traffic conditions representative of those on interstate highways in Nebraska. The procedure and results of the benefit-cost analysis are presented in this chapter.

PROCEDURE

The benefit-cost analysis involved the assessment of the net benefits associated with using the alternative work zone control strategy instead of the NDOR Merge in advance of a lane closure on a rural four-lane interstate highway. The following four alternatives were included in the analysis:

1. Indiana Lane Merge
2. Late Merge
3. Enhanced Late Merge
4. "Smart" Work Zone

The Enhanced Late Merge is a traffic-responsive form of the Late Merge. During low to moderate traffic volumes, early merging operations like the NDOR Merge are in effect. When traffic volumes are above a predetermined threshold, the Late Merge is in effect. Variable message signs would be used to effect the merge control based on the level of traffic flow detected by traffic sensors. It is envisioned that the variable message signs and traffic sensors would be deployed on the approach to the lane closure in a manner similar to that used to deploy the DO NOT PASS WHEN FLASHING signs in the Indiana Lane Merge.

The "Smart" Work Zone, as described in Chapter 3, is capable of detecting congestion and providing real-time advisory information to travelers encouraging them to divert to an alternate route. The "Smart" Work Zone can be used in conjunction with either the NDOR Merge or the Late Merge. For the purpose of this analysis, it is assumed that it is used in combination with the Late Merge, which has a higher capacity than the NDOR Merge.

The benefits and costs were determined for different combinations of ADTs and truck percentages. The directional ADT ranged from 15,000 to 28,000 vpd, and the truck percentage ranged from 0 to 50 percent. These ranges are assumed to include the ADTs and truck percentages expected on the interstate in Nebraska during the next 20 years. The results of the analysis were used to identify the most cost-effective work zone control strategies for these traffic volumes.

Benefits

The savings in road user costs were the benefits used in this analysis. The road user costs included were those associated with reductions in travel time and accidents attributed to the alternative control strategies.

Travel Time Cost Savings

The travel time cost savings are the monetary value of the travel time saved by all road user during a specified time period. The value of travel time is a function of vehicle type. For passenger cars, the value of travel time primarily depends on the purpose of the trip. For this study, an average value of all trip types was used. For trucks, the unit value of travel time depends primarily on the drivers' wage rates and the value of the transported goods. Again, average values were used for the unit values of time for trucks. The costs used in the benefit-cost analysis were those recommended by the American Association of State Highway and Transportation Officials (AASHTO) (*22*). These unit costs were updated to 1999 values according to the updating procedure recommended by AASHTO (*22*). The 1999 unit values of time used were $8.54 per hour for passenger cars and $18.33 per hour for trucks. The unit cost for trucks is a weighted average of the unit values of time recommended by AASHTO for single-unit and combination trucks. The weights were determined from an assumed traffic composition of 65 percent passenger cars, 5 percent single unit trucks and 30 percent combination trucks, which is representative of rural interstate highways in Nebraska *(23)*.

The travel time cost savings were computed by applying the updated unit time costs to the travel time delay reductions experienced with each alternative work zone control strategy. The delay for each alternative was computed using the demand-capacity method of delay analysis. For each ADT, 24 hourly traffic demands were generated using a traffic distribution representative of the daily hourly percentages of traffic on I-80 in Nebraska, which was the average of the daily hourly percentages measured by the NDOR traffic recorder stations on I-80 (*23*). The delay was expressed in terms of vehicle hours per day. The travel time delay reduction for an alternative was computed as follows:

$$\Delta D_i = D_{NDOR} - D_i \quad \textbf{(6-1)}$$

where, ΔD_i = travel time delay reduction provided by alternative i (vehicle hours/day)
D_{NDOR} = travel time delay with the NDOR Merge (vehicle hours/day)
D_i = travel time delay with alternative i (vehicle hours/day)

The capacity values and traffic diversions used in the analysis are shown in Table 6-1. Except for the Enhanced Late Merge, these capacities were determined from the field studies as described in Chapter 5. The capacity of the Enhanced Late Merge was assumed to be 5 percent higher than that of the Late Merge because of its traffic-responsive features.

TABLE 6-1 Capacities of the Work Zone Control Alternatives.

Work Zone Control Strategy	Capacity (pcph)	Traffic Diversion (percent)
NDOR Merge	1,460	-
Indiana Lane Merge	1,540	-
Late Merge	1,730	-
Enhanced Late Merge	1,820	-
"Smart" Work Zone	1,730	15

Accident Cost Savings

The accident cost savings result directly from the reduction of vehicular exposure to congested periods. When a work zone's capacity is increased and/or its traffic demand is reduced, the frequency and duration of congested periods are likewise reduced, which in turn reduces the risk of congestion-related accidents. The reduction in accidents provided by an alternative was computed as follows:

$$\Delta A_i = A_{NDOR} - A_i \qquad \textbf{(6-2)}$$

where, ΔA_i = reduction in the number of accidents per day due to congestion with alternative i
A_{NDOR} = number of accidents per day due to congestion with the NDOR Merge
A_i = number of accidents per day due to congestion with alternative i

The accident rate used to estimate the number of accidents associated with each alternative and the NDOR Merge was computed using a base rate of 85.6 accidents per million vehicle miles, which is the statewide accident rate on interstate highways in Nebraska in 1997 (*24*). This rate was multiplied by a factor of 1.34, to account for the 34 percent higher accident rate in work zones found in previous studies (*25*). It was then multiplied by 0.13 to account for the percentage of accidents found to occur during periods of congestion (*26*). The resultant accident rate was multiplied by the vehicle exposure to congestion to obtain the number of accidents per day due to congestion. The number of vehicles exposed to congestion was determined from the demand-capacity delay analysis.

The average unit cost of a work zone accident was determined by taking a weighted average of the fatality, personal injury and property-damage-only accidents occurring in work zones (*25*). This resulted in a unit accident cost of $69,963. The accident reduction for an alternative was then multiplied by this unit accident cost to obtain the accident cost savings per day.

Costs

The costs used in the benefit-cost analysis are the additional expense of the alternative work zone control strategies above the cost of the NDOR Merge. The additional costs were estimated based on information obtained from vendors, NDOR and the literature. The costs of some of the items (*e.g.*, arrow boards and signs) were provided in terms of daily rental charges. The first costs, including installation, were provided for items such as the system components of the Indiana Lane Merge and "Smart" Work Zone. The first cost of the Enhanced Late Merge was assumed to be the same as that for the Indiana Lane Merge. The first costs were annualized over the service life using a 10-percent interest rate and a zero salvage value. The service life for the Indiana Lane Merge, Enhanced Late Merge, and "Smart" Work Zone was assumed to be 10 years. A shorter, one-year service life was assumed for pavement markings. The additional costs of the alternatives are shown in Table 6-2.

TABLE 6-2 Annualized Additional Costs.

Work Zone Control Strategy	Annualized Additional Cost ($/day)
Indiana Lane Merge	120
Late Merge	6
Enhanced Late Merge	120
"Smart" Work Zone	230

RESULTS

The net benefits of the alternatives were determined for the range of ADTs and truck percentages by subtracting their additional costs from their benefits. A breakeven analysis was also performed to determine the most cost-effective alternatives over the range of traffic conditions considered.

Net Benefit

The daily net benefits provided by the alternative work zone control strategies for truck percentages from 0 to 50 percent are shown in Figure 6-1. At directional ADTs below 16,000 to 20,500 vpd, depending on truck percentage, there is no benefit of using any of the alternative work zone control strategies, because the traffic demands at these ADTs do not exceed the capacity of the NDOR Merge. The thresholds where the alternative work zone control strategies begin to provide positive net benefits depend on the demand-capacity ratio, which is a function of the truck percentage. Figure 6-1 indicates that the "Smart" Work Zone has the highest net benefit, because of the substantial reduction in delay it provides due to traffic diversion. However, it should be noted

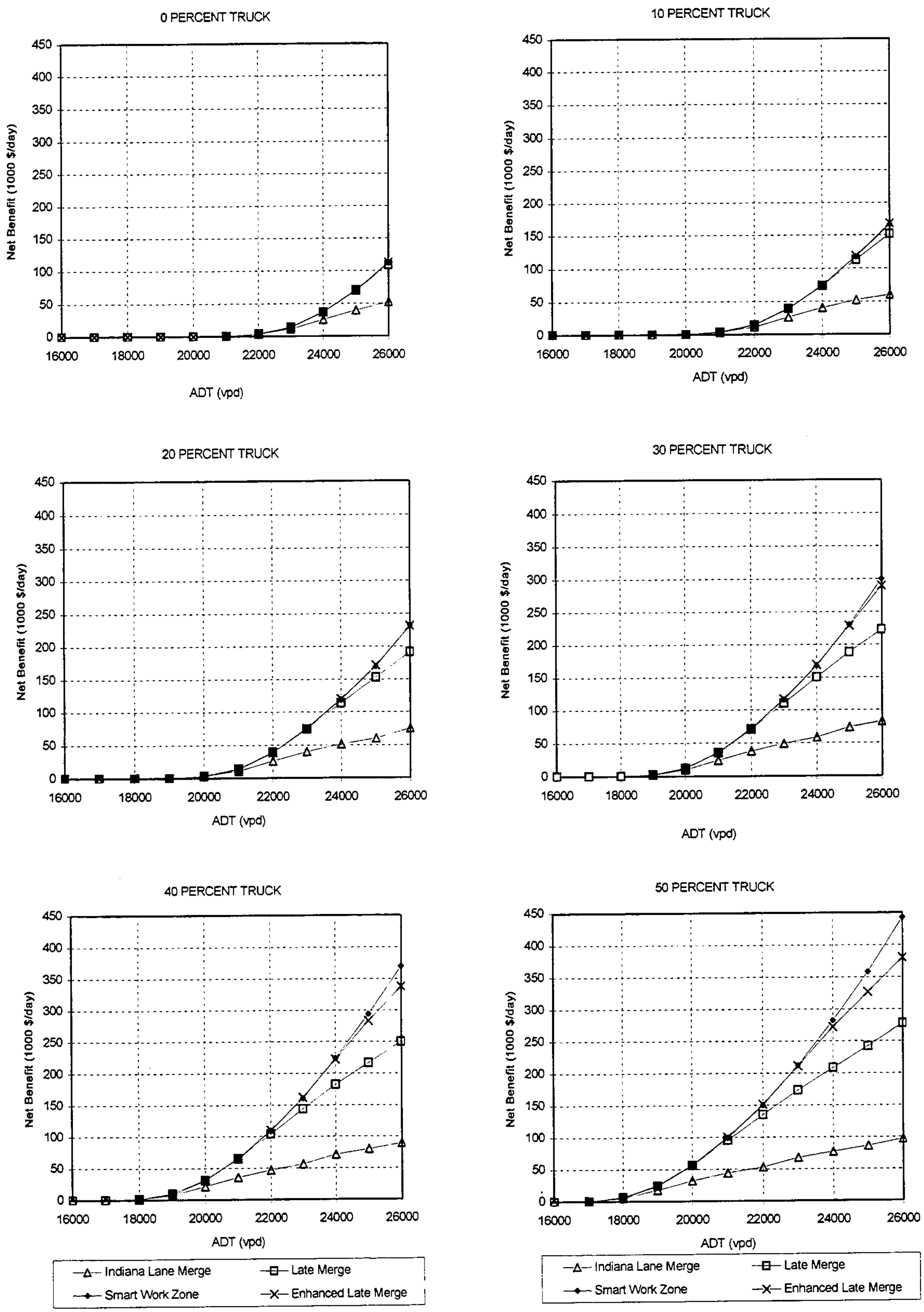


FIGURE 6-1 Daily Net Benefits of Alternative Work Zone Control Strategies.

that these results do not account for the travel time of the diverted traffic, which would depend on the length and capacity of the alternative routes available. Therefore, the net benefits for "Smart" Work Zones must be reduced by the additional travel time and accident costs associated with the diverted traffic on the alternate route when applying the results of this analysis to a particular work zone. Also, the 15-percent traffic diversion assumption may not be true in some cases.

The Late Merge and the Enhanced Late Merge provide significantly higher net benefits than the Indiana Lane Merge for all ADTs above 20,000 vph. Thus, both Late Merge strategies are more cost-effective than the Indiana Lane Merge.

Breakeven Analysis

The use of an alternative work zone control strategy is justified only if the road user cost savings exceed the additional costs of the system. A breakeven analysis was performed to determine the traffic conditions for which each alternative strategy would be the most cost-effective. The results of the breakeven analysis are shown in Figure 6-2. The combinations of ADT and truck percentage for which each alternative is the most cost-effective strategy are represented by the four regions shown.

For example, the NDOR Merge is the most cost-effective strategy for directional ADTs below 16,000 to 20,500 vpd depending on the truck percentage. Therefore, for any traffic conditions falling in this region, the use of an alternative merge strategy would not be justified. The other three strategies are the most cost-effective at higher ADTs and truck percentages. The "Smart" Work Zone is the most cost-effective at the highest levels of ADT and truck percentage.

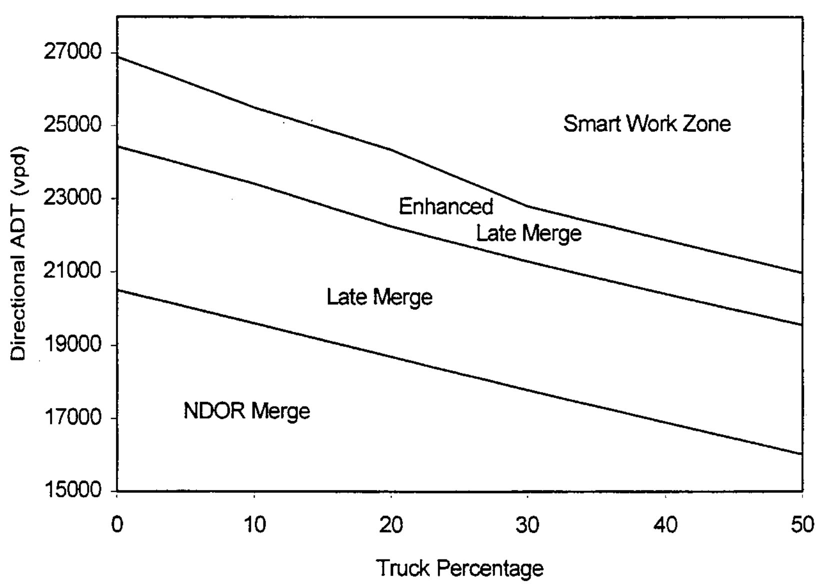


FIGURE 6-2 Most Cost-Effective Alternatives

Chapter 7

CONCLUSIONS AND RECOMMENDATIONS

The overall objective of the research presented in this report was to find better ways to control traffic at work zones on rural interstate highways. The primary focus was on improving the safety and efficiency of the merging operations in advance of lane closures. Thus, the research involved the identification and evaluation of alternative strategies designed to control traffic speeds and merging operations in advance of lane closures. Twelve alternatives were identified and evaluated using computer simulation. In addition, field evaluations of the NDOR Merge and two alternatives, the Indiana Lane Merge and Late Merge, were also conducted. A benefit-cost analysis of the alternatives was conducted to identify the most cost-effective alternatives over the range of traffic volumes and truck percentages expected on rural interstate highways in Nebraska over the next 20 years. The conclusions and recommendations of the research are presented in the chapter.

CONCLUSIONS

Based on the findings of the research, the following is concluded regarding the NDOR Merge and alternatives for improving the safety and efficiency of the merging operations in advance of lane closures on rural four-lane interstate highways:

1. Merging operations in advance of a lane closure are more efficient and safer with the Indiana Lane Merge and the Late Merge than they are with the NDOR Merge, especially at higher traffic volumes.

2. The Indiana Lane Merge and the Late Merge have higher capacities than the NDOR Merge. Therefore, congestion in advance of a lane closure would occur less often and for shorter periods of time with these alternatives than it would with the NDOR Merge.

3. The signing used to effect the Late Merge must restructure drivers' expectancies based on their prior experience at conventional lane closures, in order for the full potential of the Late Merge to be realized. Research is needed to develop an effective signing plan for the Late Merge.

4. Trucks have more difficulty when merging from the left lane to the right lane than when merging from the right lane to the left lane. This may have accounted for some of the ambivalence truck drivers expressed toward the Late Merge when interviewed at the study site where the left lane was closed. Research is needed to develop guidelines for the design of the merge point of the Late Merge.

5. The effectiveness of the Late Merge could be improved by using traffic sensors and dynamic signing to make it traffic responsive so that it would only go into effect when traffic volumes are above a predetermined threshold prior to the onset of congestion. The NDOR Merge would be in effect when traffic volumes are below the threshold. Research is needed to demonstrate the Enhanced Late Merge and develop guidelines for its implementation.

6. "Smart" Work Zones can provide substantial improvements in the safety and efficiency of merging operations due to traffic diversion. However, the magnitude of these improvements depends on the availability and capacity of alternate routes and the percent of traffic that diverts to them.

7. The most cost-effective strategy depends on the ADT and truck percentage. As shown in Figure 6-2, the NDOR Merge is the most cost-effective strategy at the lowest ADTs, and the "Smart" Work Zone is the most cost-effective strategy at the highest ADTs. The Late Merge and the Enhanced Late Merge are the more cost-effective strategies at the mid-range of the ADTs.

8. The Indiana Lane Merge is never the most cost-effective alternative over the range of traffic conditions expected on interstate highways in Nebraska over the next 20 years.

RECOMMENDATIONS

Based on the conclusions of the research, the following recommendation are made for improving the safety and efficiency of merging operations in advance of lane closures on rural four-lane interstate highways in Nebraska:

1. The type of merge control used in advance of lane closures should be selected based on the directional ADT and the truck percentage according to Figure 6-2. This figure shows the most cost-effective alternative over the range of traffic conditions expected on interstate highways in Nebraska over the next 20 years.

2. Research should be conducted to develop guidelines for the more effective signing of the Late Merge and to improve the design of its merge point.

3. Research should be conducted to develop guidelines for the use of "Smart" Work Zones which consider the traffic conditions on the alternate routes.

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APPENDIX A

Literature Review

Category	Abstract	Reference
1	The findings of a limited study aimed at examining the basic characteristics freeway traffic flow at construction zones are presented. The intent is to expand the scope of previous research efforts in this area, which have focused on the determination of point estimates of work zone capacity, under a variety of freeway lane configurations upstream of and in the vicinity of the work area. Field studies conducted in Illinois, encompassing more than 21,000 vehicle observations, were used to examine the entire range of the speed-flow relationship in the open lane of traffic. A normalizing procedure was devised to isolate and quantify the impact of work zone activity descriptors, such as the location of work relative to the traveled lanes, crew size, equipment, and other pertinent parameters, on the observed traffic speed. It was found that the effect of work activity on traffic flow is significant in periods of (a) high approach flow rates, (b) high truck percentages, and (c) intense work activity near the traveled lanes.	N. M. Rouphail. and G. Tiwari. Flow Characteristics at Freeway Lane Closures. *Transportation Research Record 1035*, TRB, National Research Council, Washington, D.C., 1985, pp. 50-58.
1	QUEWZ is a computer model that was developed In 1982 as a tool for planning and scheduling freeway work-zone operations. The model analyzes traffic flow through lane closures in freeway work zones and estimates the queue lengths and additional road user costs that would result. Several applications of the model are reported and two enhancements that have been made to improve its utility and accuracy are documented. One enhancement is an analysis option to determine acceptable schedules for alternative lane-closure configurations based on a motorist-specified maximum acceptable length of queue or delay. The second enhancement is an algorithm to account for the natural diversion of traffic away from the freeway work zone to unspecified alternative routes.	R. A. Krammes, C. L. Dudek, and J. L. Memmott. Computer Model for Evaluating and Scheduling Freeway Work-Zone Lane Closures. *Transportation Research Record 1148*, TRB, National Research Council, Washington, D.C. 1987, pp. 18-24.
1	Stochastic queuing methods are often applied to highway systems to estimate performance characteristics such as delay and queue length. Inherent in stochastic queuing methods is the assumption that the system in question operates at steady state for the duration of the analysis period. The validity of this assumption with respect to traffic-flow facilities is, at times, in question. It is therefore somewhat surprising that the vast body of literature concerned with the application of stochastic queuing methods for the assessment of highway operation includes very little discussion on the relevance of the steady-state assumption. This paper presents a simulation-based methodology for evaluating the appropriateness of the steady-state assumption. The methodology is demonstrated using a particular type of highway facility-a two-lane highway work zone. Application of the methodology suggests that the assumption of steady-state operation may not always be reasonable and, as such, illustrates the potential need to investigate the steady-state tendencies of a facility type prior to exploiting stochastic queuing techniques.	T. Tae Son, M. J. Cassidy, and S. M. Modanat. Evaluating Steady-State Assumptions for Highway Queuing Systems. *Journal of Transportation Engineering*, v 121, n 2, March/April 1995, pp. 182-190.
1	This paper presents a model of traffic on a highway based on the macroscopic description of traffic as a compressible fluid. We take the computationally efficient model of Papageorgiou and test it on field data. We extend the model to flow under the influence of traffic-obstructing incidents. In applications where the interest is in mass phenomena and real time computation, a macroscopic model is preferable over microscopic models. This model also permits systematic parameter identification, which makes it more useful for real traffic systems. The influence of incidents on the highway is included in the model and it is possible to tune its parameters for flow under incidents. This allows the model to compute the effect of incidents on flow capacity using field data.	K. Sanwal, K. Petty, J. Walrand, and Y. Fawaz. An Extended Macroscopic Model for Traffic Flow. *Transportation Research Part B*, v30, n1, 1996. pp. 1-9.
1	We will herein describe a method for managing traffic flow on roads that will help alleviate congestion. We have developed a road traffic simulator in which each vehicle can change route so as to reduce travel time in accordance with travel time information provided. The simulator simulates the so-called Q-V relation, which means the average velocity on a link is determined by the quantity of the traffic flow non-linearly. Using this traffic simulator, we have evaluated an actual traffic network both with and without the traffic information. The delay in supplying information reduces the performance of the system in our study at this particular location. Generally, the greater the number of locations for provision, the better. However, there is an optimum number that provides for fairly good performance in a relatively small number of places. This optimum information provision locations is resolved using the above-mentioned traffic simulator.	T. Yokota, M. Hotta, K. Takahashi, and T. Nagai. *Dynamic Traffic Simulation for Controlling Traffic Flow.* Proceedings of the IEEE-IEE Vehicle Navigation and Information Systems Conference 1993. IEEE Service Center, Piscataway, NJ, 1993, pp. 259- 263.

Category	Abstract	Reference
1	Work zone capacity values for rural and urban freeways without continuous frontage roads were defined and determined. Data were collected using Nu-Metrics counters and classifiers at 24 work zones in North Carolina. The research included analysis of speed-flow behavior, evaluation of work zone sites based on lane configuration and site location, and determination of the location within the work zone where capacity is lowest. It was shown that the intensity of work activity and the type of study site (rural or urban) strongly affected work zone capacity. The data suggested that the location where capacity is reached is also variable based on the intensity of work. For heavy work in a two-lane to one-lane work zone configuration, the capacity values proposed at the active work area are approximately 1,200 vehicles per hour per lane for rural sites and 1,500 vehicles per hour per lane for urban sites. It recommended that distant volumes be used when queue behavior in a freeway work zone is analyzed. The collapse from uninterrupted flow (designated work zone capacity) and the lower queue-discharge volume both should be considered.	K. K. Dixon, J. E. Hummer, and A. R. Lorscheider. Capacity for North Carolina Freeway Work Zones. *Transportation Research Record 1529*, TRB, National Research Council, Washington, D.C., September 1996, pp. 27-34.
1	The five fundamentals of traffic control are often the last thing incorporated into any road project, according to Richard Gumtau, highway safety programs engineer for the U.S. Department of Transportation. 1. Traffic safety in construction zones should be part of the planning through design and construction. 2. Traffic movement should be inhibited as little as possible. 3. Motorists should be guided in a clear and positive manner, and flaggers should be trained and certified. 4. Routine inspection of traffic control elements should be undertaken. 5. The maintenance of roadside safety requires constant attention to avoid an increase in hazardous situations.	R. Gumtau. Richard Gumtau on Traffic Control and Work Zones. *Better Roads*, v 63, n 9, Sept. 1993, p. 31.
1	With a dynamic traffic assignment model real-time control algorithms are derived for an alternative route guidance system. As traffic model a fluid dynamic description of traffic flow is presented which uses a specific speed density relation and an anticipation of traffic conditions downstream. The macroscopic traffic flow model is solved numerically with initial and boundary conditions including links and modes derived from actual measurements and with data for compliance rates of alternative route indications via variable message signs. For three actual alternative route guidance systems in Germany, the application of the real-time control algorithms is demonstrated. From these examples data are gathered, compliance rates are derived and the advantages for different traffic situations of the alternative routing strategy are presented.	R. D. Kuehne. *Real-time Traffic Control for Alternative Route Guidance Systems Based on the Dynamic Assignment Model.* Proceedings of the International Conference on Applications of Advanced Technologies in Transportation Engineering 1996. ASCE, New York, NY, 1996, pp. 563-567.
1	A methodology for the detailed evaluation of measured freeway traffic stream features is presented. The method compares cumulative vehicle arrival curves at multiple locations, and empirical data illustrate traffic flow dynamics. However, conclusions with regard to traffic flow features will not be drawn until ongoing research is completed. The paper presents a methodology for performing a detailed assessment of features of measured freeway traffic stream. Application of the proposed methodology identifies how disturbances propagate in time and space. Empirical data are used to present examples of traffic flow features revealed by the proposed method and to illustrate the methodology's advantages over conventional techniques for evaluating freeway data. The paper is methodological in nature; the authors, therefore, defer drawing conclusions on traffic flow dynamics until the ongoing research is completed.	M. J. Cassidy and J. R. Windover. Methodology for Assessing Dynamics of Freeway Traffic Flow. *Transportation Research Record 1484*, TRB, National Research Council, Washington, D.C., 1995, pp. 73-79.
1	An important aspect of a highway work zone is the lane-closure strategy and the movement of traffic through the work zone. As part of the evaluation to determine the effects of different lane-closure strategies (e.g., one-, two-, or three-lane closures on a four-lane section), the additional costs to vehicle users should be considered. It is therefore necessary to have a model that will improve the accuracy of user cost estimates resulting from the forced movement through a restricted work zone. A computer model, Queue and User Cost Evaluation of Work Zones (QUEWZ), developed to estimate the additional user costs resulting from lane closures in one or both directions of travel is described. User costs can be estimated when one or more lanes are closed in just one direction of travel or when a crossover is used. Hourly as well as daily user costs are estimated, and when vehicle demand exceeds capacity, the model also estimates the length of queue. The model is designed specifically for freeway conditions, but it can be used in other situations if appropriate adjustments are made in the input data. Two vehicle types are used in the model--passenger cars and trucks.	J. Memmott and C. Dudek. Queue and User Cost Evaluation of Work Zones (QUEWZ). *Transportation Research Record 979*, TRB, National Research Council, Washington, D.C., 1984, pp. 12-19.

Category	Abstract	Reference
1	This paper presents a theory for automated traffic flow, based on an abstraction of vehicle activities like entry, exit and cruising, derived from a vehicle's automatic control laws. An activity is represented in the flow model by the space and time occupied by a vehicle engaged in that activity. The theory formulates Traffic Management Center (TMC) plans as the specification of the activities and velocity of vehicles, and the entry and exit flows for each highway section. We show that flows that achieve capacity can be realized by stationary plans that also minimize travel time. These optimum plans can be calculated by solving a linear programming problem. The theory permits the study of transient phenomena such as congestion, and TMC feedback traffic rules designed to deal with transients. We propose a "greedy" TMC rule that always achieves capacity but does not minimize travel time. We undertake a microscopic study of the "entry" activity, and show how lack of coordination between entering vehicles and vehicles on the main line disrupts traffic flow and increases travel time. We conclude by giving some practical indication of how to obtain the space and time usage of activities from vehicle control laws. Finally, we illustrate the concepts presented in this paper with two examples of how the model is used to calculate the capacities of a one-lane automated highway system. In one example we study market penetration of adaptive cruise control and in the second example we study the effect of platooning maneuvers in a platooning architecture for AHS.	M. Broucke and P. Varaiya. A Theory of Traffic Flow in Automated Highway Systems'. *Transportation Research Part C*, v4, n4, 1996, pp. 181-210.
1	A method is presented that extends the U.S. *Highway Capacity Manual* (HCM) delay progression factor method to the prediction of queue length, queue clearance time, proportion queued (stopped), and queue move-up rate. These predictions are achieved by the introduction of an additional progression factor and adoption of the HCM overflow term adjustment factor. providing a simple method to allow for the effects of platooned arrivals on the performance of coordinated signalized intersections. The method is useful at the level of basic capacity and performance analysis of a single intersection where detailed platooned arrival patterns generated at upstream signal stop lines are not available. The arrival types defined by the HCM as the basic input to define the characteristics of platooned arrivals are adopted for use in calculating the additional progression factor in the same way as the original HCM progression factor for delay. It is assumed that the reader has a good knowledge of the subject area.	R. Akcelik. Progression Factor for Queue Length and Other Queue-Related Statistics. *Transportation Research Record 1555*, TRB, National Research Council, Washington, D.C., 1997, pp. 99-104.
1	Highway congestion has in recent years become a pervasive problem for urban and suburban areas alike. The concept of Automated Highway Systems is based on the belief that integration of sensing, communication, and control technologies into vehicles and highways can lead to a large improvement in capacity and safety without requiring a significant amount of additional highway right-of-way. A fundamental determinant of automated Highway Systems capacity is the vehicle-following rule, the rule that governs the behavior of vehicles traveling along a common lane (eg., the spacing between any two longitudinally adjacent vehicles). Vehicle following affects the longitudinal capacity (achievable flow within a lane), the lateral capacity (achievable flow between lanes) and the conflicting relationship between the longitudinal flow and lateral capacity. The issues are investigated by developing probabilistic models for vehicle / platoon and gap distributions, for vehicles that travel in platoons, in slots, or as free-agents. Mathematical models are also developed to estimate the completion time of a lane change, which can be used as a surrogate for the lateral capacity. Numerical results for the three major vehicle-following rules and their comparison are also provided.	H. Tsao, R. Hall, and I. Chatterjee. Analytical Models for Vehicle/Gap Distribution on Automated Highway Systems. *Transportation Science*, v31, n1, February 1997, pp. 18-33.
1	For a freeway having various entrance and exit ramps, the methods described in Part I are used to relate the cumulative flow curve at any junction to the net cumulative entrance flow at this junction, and the cumulative flow curves for the freeway at the next upstream junction and/ or the next downstream junction. If the type of flow-density relations typical of freeway traffic are idealized by a triangular shaped curve with only two wave speeds, one for free-flowing traffic (positive) and the other for congested traffic (negative), then the relationship is easy to evaluate. The cumulative flow curve at the junction is simply the lower envelope of a translation of the cumulative curve from upstream and a different translation of the cumulative curve from downstream. This relationship is the basic building block for a freeway flow prediction model described in Part III.	G. Newell . A Simplified Theory of Kinematic Waves in Highway Traffic, Part II: Queuing at Freeway Bottlenecks. *Transportation Research Part B*, v27B, n4, 1993, pp. 289-303.

Category	Abstract	Reference
2	The risk of collision in an expressway merging process is investigated using the traffic conflict technique. The severity of conflict in a merging event is quantified by a measure that is the inverse of the time measured to collision. To determine this measure, recordings of merging events were obtained at a merging area of an expressway in Singapore over eight periods, and the arrival times of vehicles at constantly spaced intervals were subsequently extracted in the laboratory. The errors in the data-collection process were minimized by using two video cameras simultaneously in the recording process to increase the size of images and playing back the tapes at a lower speed during data extraction. The systematic errors in the data due to observers' bias were also estimated to facilitate data adjustment. Based on the adjusted data, the computed measure from about 200 merging events in each observation period was found to be best fitted by the mixed Weibull distribution. Using the tail end of the distribution, the probability of near accident per merge in each period was estimated	H. C. Chin, S. T. Quek and R. L. Cheu. Traffic Conflicts in Expressway Merging. *Journal of Transportation Engineering*, v117, n6, November/December 1991, pp. 633-643.
2	This paper presents a queue-theoretical model for describing traffic flow on a dual two-lane motorway. The model is based on the theory of stationary Markov processes and is closely related to data collection methods made possible by specially developed recording equipment. The model is based on a description of the driver's behavior in traffic. The individual driver alternates between driving under free-flow conditions (state F) at his or her desired speed and without delay and driving in a queue (state K) with consequent delay. To escape from or possibly entirely avoid a queue, a driver must change lanes (alternate between lane 1 and lane 2). The behavior of the driver is thus described by a variable that assumes the discrete values 1 F, 1 K, 2F, and 2K. This process can be described as a Markov process. The reactions of individual drivers are summed up in a comprehensive description of the average driver's behavior, so that the road traffic model developed is an example of a macrostochastic model. A technique has been developed by which the parameters in the Markov process can be estimated from the collected data, and the paper describes how the model becomes part of a detailed investigation into the vital conditions affecting motorway traffic, e.g., capacity, relationship between speed and traffic volume, and the drivers' use of the motorway.	J. Rørbech. Multilane Traffic Flow Process: Evaluation of Queuing and Lane-Changing Patterns. *Transportation Research Record 596*, TRB, National Research Council, Washington, D.C., 1976, pp. 22-29.
2	The study dealt with a proposed taper length formula that yields shorter tapers at design speeds below 96 km/h (60 mph) than does the existing formula (L=WS, when S is in mph). This paper reports on a direct comparison of traffic operations using both the standard and proposed taper lengths in the same construction zones. Speed, erratic maneuvers, traffic conflicts, and lane encroachment data were collected at four sites, day and night, for a variety of design speeds and taper lengths. The analyses of the data collected do not imply that the proposed taper lengths are more hazardous than the standard taper length. Use of the proposed length did not produce a greater number of erratic maneuvers and slow-moving vehicle conflicts than did the standard or existing taper length. There was no indication that the proposed taper lengths resulted in a greater number of passenger vehicle or truck encroachments on adjacent lanes.	J. Graham, D. Harwood, and M. Sharp. Effects of Taper Length on Traffic Operations in Construction Zones. *Transportation Research Record 703*, TRB, National Research Council, Washington, D.C., 1979, pp. 19-24.
2	Several researchers have analyzed queuing patterns at bottleneck sites on freeways during the morning peak. However, all previous studies have assumed that each commuter passes only one bottleneck during his commuting trip. Here, we consider the possibility that some commuters pass two bottlenecks on their way to work. The objective is to obtain cumulative arrival curves at each of the two bottlenecks, given who passes both bottlenecks and who passes only one, and their desired arrival times at their work places (work starting times). Each commuter using the freeway is assumed to have the same travel cost function which consists of time-dependent costs due to queueing delay (waiting time in a queue) and schedule delay (the time difference between his actual and desired arrival time at the work place). Commuter trips are assigned temporally so as to establish an equilibrium in which each commuter seeks to minimize his travel cost. The queue evolutions illustrate a service priority at the downstream bottleneck in favor of commuters passing only the downstream bottleneck. One of the countermeasures for this equity problem in the service priority would be to meter the favored commuters.	M. Kuwahara. Equilibrium Queueing Patterns at a Two-Tandem Bottleneck during the Morning Peak. *Transportation Science*, v 24, n 3, August 1990, pp. 217-229.

Category	Abstract	Reference
2	Observations of flow rates much higher than 2,000 passenger cars per hour per lane and the recent revision of the multilane highway chapter in the *Highway Capacity Manual* have led to questioning the current value of freeway capacity and the speed-flow relationship. An analysis of free-flow and queue discharge flow rates at three freeway bottlenecks in Texas found less variability in queue discharge flow rates than in free-flow rates. Average free-flow rates ranged from 2,096 to 2,210 vehicles per hour per lane (vphpl) across all lanes, whereas queue discharge flow rates averaged approximately 2,175 vphpl for the study sites. In addition, higher flows did not occur in free-flow conditions in all cases. As a result of lane interaction, some lanes are prematurely transitioned into queue discharge without reaching high flow rates in free-flow conditions.	J. Ringert and T. Urbanik II. Study of Freeway Bottlenecks in Texas. *Transportation Research Record 1398*, TRB, National Research Council, Washington, D.C., 1993, pp. 31-41.
2	A study of freeway lane closures at work zones is described. It involved the development of a microscopic computer-simulation model. Vehicles in platoons are controlled by a car-following rule. The merging behavior is controlled by the information provided by the traffic-control devices, by personal preference for early or delayed merge, and by the availability of gaps in the open lane. The prescription of personal preference was based on a driver survey. The model also checks for the possible obscuring of signs by large vehicles. Field tests produced varied results, but average speeds and throughput (vehicle miles per hour squared) generated by the model fit between the classical Greenshield's model and those calculated by the 1980 revision of the Highway Capacity Manual. A factorial simulation study was conducted to investigate traffic behavior under a variety of conditions, represented by different volume levels, traffic compositions, merging preferences, speed control and compliance, and advance-warning distances. Delay and standard deviation of speed at the taper were generated for each factor-level combination. The results generally confirmed what was expected. Noteworthy is the indication that full compliance with a reduced speed limit of 45 mph would increase delayed merges within the taper area in the volume range simulated.	Z. A. Nemeth and N. M Rouphail. Lane Closures at Freeway Work Zones: Simulation Study. *Transportation Research Record 869*, TRB, National Research Council, Washington, D.C., 1982, pp. 19-25.
2	This paper presents a methodology for optimizing performance of a traffic system on the basis of simulated observations of its microscopic behavior. The method integrates simulation and optimization sub-models for describing traffic flow on urban freeway lane closures. The stochastic nature of traffic is accounted for in determining the true system response to traffic control variables. The simulation sub-model has been validated at a series of work sites in the Chicago area expressway system. The optimization sub-model optimizes a single objective function subject to a set of linear constraints. Preliminary model applications included the determination of an optimum merging strategy to be adopted by traffic entering the work zone in lanes to be closed for traffic. The model recommendation yielded the lowest average travel time in the work zone and, interestingly, did not incorporate many early merges; the latter is often viewed as a desired merging strategy. In addition, the optimum merging strategy varied with the traffic flow level entering the work zone and with the character of the objective function to be optimized.	R. M. Mousa, N. M. Rouphail, and F. Azadivar. Integrating Microscopic Simulation and Optimization: Application to Freeway Work Zone Traffic Control. *Transportation Research Record 1254*, TRB, National Research Council, Washington, D.C., 1990, pp. 14-25.
2	Research conducted to explore the effects of natural diversion on traffic conditions and travel patterns upstream of temporary work zone lane closures on high-volume urban freeways in Texas is described. Specific objectives were to explore how natural diversion affects traffic volumes at the exit and entrance ramps upstream of the lane closures and the interrelationships between the freeway and frontage road operating conditions that develop at a closure and the amount of natural diversion that occurs. The field studies showed that the rate of queue growth upstream of the short-term lane closures diminished significantly after the first hour at each site. Eventually, the queues approached a balanced state in which the upstream end of the queue almost stationary. This stabilization was due to significant reductions in entrance ramp volumes both upstream of the freeway queue and within the limits of queuing, as well as to changes in exit ramp volumes within the queue. As a result of these ramp volume changes the constrained flow rate within the queue increased as a function of the distance upstream of the actual lane closure. Using the theory of shock waves in a traffic stream it was shown that the changes in ramp volumes and resulting impact on constrained freeway flow rates within the queue were consistent with the queue stabilization process observed at each site	G. L. Ullman. Queueing and Natural Diversion at Short-Term Freeway Work Zone Lane Closures. *Transportation Research Record 1529*, TRB, National Research Council, Washington, D.C., September 1996, pp. 19-26.

Category	Abstract	Reference
2	A problem of queuing in lanes treated by Hauer and Templeton I is generalized and a solution provided through the use of some combinatorial lemmas. The taxonomy of the Hauer-Templeton model is clarified. Further areas of possible application of the ideas involved are suggested.	W. Henderson, R. W. Kennington, and C. E. M. Pearce. A Second Look at a Problem of Queueing in Lanes. *Transportation Science*, v 18, n 1, February 1984, pp. 85-93.
2	Microscopic models provide an understanding of traffic operations at the level of passage of individual vehicles. Roadway performance can be ascertained by understanding how vehicles interact with each other. Cowan's M3 headway distribution models were calibrated for the curb and median lanes of two-lane mainline freeway segments, using data captured at 14 sites. Calibration of the relationship among Cowan's M3 parameters, proportion of headways greater than a minimum of I see, and flow rate yielded exponential decay equations for each lane. The M3 models provide a source of vehicle arrivals for gap acceptance models, which may be used to quantify the ability of drivers to change lanes, for example. It was found that the parameters calibrated for each lane are suitable for use at any mainline site, independent of site-specific conditions. The proportion of small headways was found to be higher in the median lane than the curb, for all flow rates, and for both lanes lower than their respective equivalents on arterial roads with intersections. The largest bunched headway was considered to be between 2 and 3 sec. The models predicted bunching between 85 and 93 percent of median lane vehicles, and between 75 and 90 percent of curb lane vehicles, at capacity. The lesser amount of curb lane bunching reflects its use as a slower vehicle lane with greater stream friction.	J. M. Bunker and R. J. Troutbeck. Microscopic Modeling of Traffic Within Freeway Lanes. *Transportation Research Record 1510*, TRB, National Research Council, Washington, D.C., 1995, pp. 19-25.
2	The paper gives conditions which guarantee the existence of an equilibrium arrival pattern at a single bottleneck. In the model, the times at which a driver wishes to leave the bottleneck depend on the driver. The equilibrium queue length in this model always has a continuous time derivative everywhere. However, the slope of the equilibrium cumulative arrival distribution is discontinuous at the beginning and end of congestion.	M. J. Smith. The Existence of a Time-Dependent Equilibrium Distribution of Arrivals at a Single Bottleneck. *Transportation Science*, v 18, n 4, November 1984, pp. 385-394.
2	Motorists going through a bottleneck during the morning rush hour have to time their departure times to ensure they arrive to work at a reasonable time. Traffic and congestion levels at the bottleneck depend on the motorists' work schedule and the disutility of unpunctuality. This paper shows that, under certain conditions, there is only one equilibrium order of arrivals; an order under which motorists do not have an incentive to jockey for position in the queue.	C. F. Daganzo. The Uniqueness of a Time-dependent Equilibrium Distribution of Arrivals at a Single Bottleneck. *Transportation Science*, v 19, n 1, Feb. 1985, pp. 29-37.
2	Highway congestion has in recent years become a pervasive problem for urban and suburban areas alike. The concept of Automated Highway Systems is based on the belief that integration of sensing, communication, and control technologies into vehicles and highways can lead to a large improvement in capacity and safety without requiring a significant amount of additional highway right-of-way. A fundamental determinant of automated Highway Systems capacity is the vehicle-following rule, the rule that governs the behavior of vehicles traveling along a common lane (e.g., the spacing between any two longitudinally adjacent vehicles). Vehicle following affects the longitudinal capacity (achievable flow within a lane), the lateral capacity (achievable flow between lanes) and the conflicting relationship between the longitudinal flow and lateral capacity. The issues are investigated by developing probabilistic models for vehicle/platoon and gap distributions, for vehicles that travel in platoons, in slots, or as free-agents. Mathematical models are also developed to estimate the completion time of a lane change, which can be used as a surrogate for the lateral capacity. Numerical results for the three major vehicle-following rules and their comparison are also provided.	H.S. J. Tsao, R. W. Hall, and I. Chatterjee. Analytical Models for Vehicle/Gap Distribution on Automated Highway Systems. *Transportation Science*, v 31, n 1, February 1997, pp. 18-33.
2	Traditional gap acceptance functions have been estimated based on the first gap observed. In this paper we show that the critical gap of drivers is decreasing on the average, as they are waiting for an acceptable gap. Our gap acceptance function is based on a probit model which assumes a normal distribution of gaps across gaps and drivers.	H. Mahmassani and Y. Sheffi. Using Gap Sequences to Estimate Gap Acceptance Functions. *Transportation Research Part B*, v15B, 1981, pp. 143-148.

Category	Abstract	Reference
2	Aerial data were used to determine average spatial and time sizes of the accepted gaps and the lag gaps in gap-acceptance maneuvers for exiting vehicles close to their intended off-ramp and for through vehicles as a function of distance from the off-ramp. Furthermore, an attempt was made to quantify the accident risk that was assumed by each lane changer and the accident risk that was imposed by each lane changer on the lag car of the accepted gap. Results were obtained for an 8-, a 6-, and a 4-lane freeway site and for various flow levels. In general, the average spatial and time gap and lag gap sizes of gaps accepted by exiting vehicles decrease as the exiting vehicles approach the off-ramp. The corresponding average values for through vehicles show less, if any, dependency on distance from the off-ramp. Average gap and lag gap sizes of gaps accepted by exiting and through vehicles decrease with increasing flow levels. Within the assumptions made, it was found that a larger accident risk is accepted by exiting vehicles than by through vehicles in their lane changes, whereas the accident risk imposed on the lag car of the accepted gap is smaller for lane changes by exiting vehicle than by through vehicle.	J. Pahl. Gap-Acceptance Characteristics In Freeway Traffic Flow. *Transportation Research Record 409*, TRB, National Research Council, Washington, D.C., 1972, pp. 57-63.
3	The speed monitoring display is a traffic control device that uses radar to measure the speeds of approaching vehicles and shows these speeds to traffic on a digital display panel. It is intended to slow traffic by making drivers aware of how fist they are traveling. In addition, it is expected that its radar will also cause some drivers using radar detectors to slow down. The effectiveness of this device was evaluated at a work zone on an interstate highway in South Dakota. The speed monitoring display reduced mean speeds and excessive speeds on the approach to the work zone. Mean speeds were reduced by 6 to 8 km/hr (4 to 5 mi/hr, and the percentages of vehicle exceeding the advisory speed limit of 72 km/hr (45 mi/hr) were reduced by 20 to 40 percentage points. These speed reductions are greater than those reported for the use of radar alone.	P. McCoy, J. Bonneson, and J. Kollbaum. Speed Reduction Effects of Speed Monitoring Displays with Radar in Work Zones on Interstate Highways. *Transportation Research Record 1509*, TRB, National Research Council, Washington, D.C., 1995, pp. 65-72.
3	Administrators, practicing engineers, and researchers continually face highway problems on which much information already exists, either in documented form or in terms of undocumented experience and practice. Unfortunately, this information is often fragmented, scattered, and under-evaluated. Often it is unknown to the person normally responsible for making decisions related to the topic. As a consequence, full knowledge of what has been learned about a problem is frequently not brought to bear on its solution. Costly research findings may go unused, valuable experience may be overlooked, and due, consideration may not be given to recommended practices for solving or alleviating the problem. There exists a vast storehouse of information relating to nearly every subject of concern to highway administrators and engineers. Much of it resulted from research and much from successful application of the ideas of practitioners faced with problems in their day-to-day work. Because there has been no systematic means for bringing such useful information together and making it available to the entire highway community, the American Association of State Highway and Transportation Officials has, through the mechanism of the National Cooperative Highway Research Program, authorized the Transportation Research Board to undertake a continuing study, NCHRP Project 20-5, "Synthesis of Information Related to Highway Problems." This study is intended to search out and synthesize useful knowledge from all possible sources and to prepare documented reports on current practices in the subject areas of concern. Reports from this endeavor constitute an NCHRP report series, Synthesis of Highway Practice, that collects and assembles the various forms of information into single concise documents pertaining to specific highway problems or sets of closely related problems.	S. A. Sabol. *NCHRP Report 212: Continuing Project to Synthesize Information on Highway Problems.* TRB, National Research Council, Washington, D.C., July 1996, pp. 1-9.
3	The DRIVE 11 research program part-funded by the Commission of the European Communities has included several projects which have undertaken the pilot operation of real-time dynamic traffic information services. The PLEIADES project has encompassed several experiments in the U.K., France and Belgium along a corridor of strategic roads linking London with Paris, Lille and Brussels. Using the PLEIADES project as an example, this paper considers the opportunities which now exist for extensively promoting the increased availability of a new generation of real-time dynamic traff ic information services. The technical, business and institutional issues which must be addressed in order to provide fully operational services, as viewed from the U.K. organizational perspective, are also considered in the paper.	M. Hayward, H. Martin, S. Hoffman, S. Parnall, and P. Still. Future Opportunities for the Provision and use of Real-Time Dynamic Traffic Information Services. *Traffic Engineering and Control,* Nov. 1994.

Category	Abstract	Reference
3	The effectiveness of changeable message signing (CMS) devices in advance of freeway construction and maintenance zone lane closures was evaluated. Operational traffic behavior and driver interview data were gathered in four states. Before-and-after studies of baseline (no CMS) versus CMS application consistently demonstrated increased advanced preparatory lane-change activity, smoother lane-change profiles, significantly fewer late exits (within 100 ft of closure), and reduced speeds at the lane-closure point to be associated with CMS use. The most preferable CMS location was found to be 0.75 mile (1.2 km) in advance of the lane closures. Of three tested device types (one-line bulb matrix, two-line rotating drum, and three-line bulb matrix), the large, obtrusive three-line bulb matrix tended to produce more advance lane-change behavior; however, no difference in the hazardous late exit maneuvers was observed between types. All three were equally effective in eliciting speed reductions at the entrance to the lane closure. Driver interview data tended to favor the three-line device due to its greater information display capacity. Message combinations of speed, lane closure, and merge advisories were tested on the devices. Although lane-change behavior of the total traffic stream did not significantly differ between message conditions, interviewed motorists favored the speed and lane-closure message combination as being most helpful, providing most response time, and meeting information needs. The study recommends CMS applications as a supplement to standard device schemes but not as a substitution for the arrowboard. Suggested cost-efficient CMS applications involve (a) short-term closures characterized by decreased driver expectancy, lb) traffic volumes of 900 vehicles/h or greater, and (c) limited sight distance to the closure.	F. R. Hanscom. Effectiveness of Changeable Message Signing at Freeway Construction Site Lane Closures. *Transportation Research Record 844*, TRB, National Research Council, Washington, D.C., 1982, pp. 35-41.
3	The Wisconsin Department of Transportation contracted with Marquette University to research improvements in construction work zone signs. The RIGHT/LEFT LANE CLOSED and ROAD CONSTRUCTION series were selected because they are the most difficult to improve without increasing sign size above a 48-in. diamond. All signs used high-intensity retro-reflective material. Twelve test signs ",ere selected for day and night viewing by 46 observers under age 65, and 38 observers aged 65 and over. Experimental messages included rearranged legends (three to four lines) substitution of WORK for CONSTRUCTION, 18 percent stroke width increases on the inside of letters without increasing letter width. and use of Series E letters upper and lowercase [instead of all capitals as required by the *Manual on Uniform Traffic Control Devices (1)]*. The conclusion of this study was that few improvements can be made in the LANE CLOSED series without more drastic changes than those tested. In the ROAD CONSTRUCTION series, substantial improvement can be made by substituting WORK for CONSTRUCTION and increasing letter size. The 18 percent stroke-width concept resulted in no improvement and some reduction by day for younger observers. The most promising finding is the improvement possible with Series E letters because of their 20 percent increase in stroke width. Less loss of night legibility distance compared with that of day occurred with this alphabet than with any other. Further research substituting tenths of a mile for feet, which would allow larger letter size, is recommended, and field experimentation with Series E letter series under Federal Highway Administration requirements is recommended.	D. A. Kuemmel. Maximizing Legibility of Traffic Signs in Construction Work Zones. *Transportation Research Record 1352*, TRB, National Research Council, 1992, pp.
3	Changeable Message Signs (CMS) assume a key role in alleviating traffic congestion by increasing motorists awareness of the unusual traffic conditions on roadway(s). Most of the CMS's installed by agencies like the Ministry of Transportation, Ontario (MTO) and Caltrans are quite expensive, since they are required to comply with greater visibility/legibility characteristics, ability to display long messages, and low maintenance requirements. Although such stringent specifications are justifiable for high speed facilities, they may not be totally applicable to installations on the City streets, where the operating speeds are lower and more lenient routine maintenance specifications may be acceptable. The City of Pasadena has taken a lead in this initiative and is currently proceeding with the installation of low cost changeable message signs along the City streets. As a part of this project, a CMS Demonstration involving various light emitting and reflective sign technologies was organized to evaluate the visibility and legibility characteristics under different ambient lighting conditions. A summary of the demonstration results is included in this paper.	S. R. Nadriga and D. Smith. *Changeable Message Sign Options for City Street Installations.* Transportation Congress, Proceedings, v 1, ASCE, New York, NY, 1995, pp. 349-357.

Category	Abstract	Reference
3	Variable message signs are used as part of freeway management systems to provide drivers with real-time information on roadway and traffic conditions. Fiber-optics and light emitting diodes are two emerging technologies currently being marketed for use as variable message signs. As these technologies become increasingly used in freeway management systems, it is important that drivers be able to read and to comprehend their messages. This paper presents data on legibility distance, target value, and viewing comfort measured by observers as partof a comprehensive human-factors study of two light emitting diode and four shuttered fiber-optic variable message signs in Phoenix, Ariz. Data for these parameters are given for an older and a younger group of observers. The presentation of these data leads to a discussion on design considerations for fiber-optic and light emitting diode variable message signs.	J. D. Armstrong and J. E. Upchurch. Human Factors Design Considerations for Variable Message Freeway Signs. *Journal ofTransportation Engineering*, ASCE, v 120, n 2, March/April 1994, pp. 264-282.
3	Recent years have seen the introduction of many electronic signs providing dynamic information to road users. These variable message signs are, in most cases, connected together to form systems over increasingly large geographical areas, and have the opportunity to influence significant numbers of drivers. Much work is currently under way to measure the performance of such systems in order to*assess* the benefits of the investment and justify the further development of signs. The results are beginning to identify VMS-strategies that yield the best returns. They have already provoked proposals for further integration of VMS with other information system, and are highlighting institutional issues relating to sign control. This paper summarizes these results and the emerging conclusions from the work.	M. Cummings. *Electronic Sign Strategies and their Benefits.* IEE Conference Publication 1994 , n 391. IEE, Michael Faraday House, Stevenage, England, pp. 141-144.
3	In a study of driving simulators the effects on route choice and driving behavior of presenting descriptive types of information on variable message (route guidance) signs were evaluated. Subjects had to choose between a normal route to a fixed destination. which could suffer from congestion of varying severity, and an alternative route. Three modes of variable information presentation were compared: (a) length of congestion, in kilometers; (b)delays relative to normal travel times, in minutes; and(c)travel times, in minutes. The reliability of the information was also varied and could be high, intermediate, or low. Thirty-six men participated in the experiment, and every subject made 123 runs in the simulator. By presenting descriptive information, divergence levels were found that varied widely over the range from 0 to 100 percent, as a function of the actual information given. This is to be compared with the inflexibility of conventional (prescriptive) signing. User optimum was most often reached by presenting travel time information. Such information also proved to be most resistant against degradations in reliability. There was an overall increase in driving speed when descriptive information was given, and this may be interpreted as anticipatory behavior from the side of the driver to compensate for the expected delay upon finding the normal route to be congested.	W. Janssen and R. Van Der Horst Presenting Descriptive Information in Variable Message Signing. *Transportation Research Record 1403*, TRB, National Research Council, Washington, D.C., 1993, pp.
3	In an effort to improve the operations of both portable and permanent (fixed-site) variable message signs (VMSs) in Virginia, a comprehensive research effort to develop operational guidelines was undertaken. These guidelines, presented in the form of users' manuals, were based on information obtained from the literature, VMS operators, and motorists. Issues addressed by the manuals include whether to use a VMS, where to place a portable VMS, and how to design a VMS message. The manuals are not simply a list of predefined messages; instead, they are composed of concise, readable modules designed to guide an operator through the thought process required to use a VMS effectively. An operator follows a logical decision tree as each module is completed, allowing effective use of the VMS as well as training the operator for use of the device. Key lessons learned in developing two such manuals for portable and permanent VMSs are highlighted. On the basis of theoretical calculations and motorists' experiences, it is strongly recommended that a VMS use no more than two message screens. A single message screen is preferred. VMSs should be used only to advise drivers of changed traffic conditions and to convey specific traffic information concisely. Because of limited information capabilities, VMSs should be used in conjunction with other means of communication such as highway advisory radio and static signs. Most importantly, it is crucial that credibility be maintained. Incorrect information can have disastrous consequences on VMS effectiveness.	J. S. Miller, B. L. Smith, B. R. Newman, and M. J. Demetsky. Effective Use of Variable Message Signs: Lessons Learned Through Development of Users' Manuals. *Transportation Research Record 1495*, TRB, National Research Council, Washington, D.C., 1995, pp. 1 - 8.

Category	Abstract	Reference
3	Choice of a local control device is an important aspect of using variable message signs. During the planning stages of one such telecommunications-based system, planners decided that an emergency control function was needed to assure system continuity, says William Wellman, Engineering Tech Five, Office of Traffic, Maryland State Highway Administration. The Administration operates under the Department of Transportation. A review of federally funded overhead systems throughout the United States revealed that most systems pre sentry constructed use manual forms of message control at the roadside, Wellman says. These manual means usually incorporate toggle switch or thumb wheel switch patterns, which recall messages programmed into read-only memories (ROM). When messages are selected, they are then displayed on the overhead message board. But, these message displays are usually limited to p re-burned selections. This means that the system is reduced in its efficiency t is, in effect, dependent on the using agency's capability to foretell the nature of needed emergency messages, leaving no options for unpredicted or emergency message requirements. More often than not, the operating agency using such a system was new to variable sign use, the study determined, and had to develop new message as their operations progressed. If they had chosen silicon, this often presented a roadblock to system updates. This problem may have caused some systems to be turned off prematurely.	Choosing s Local Control for Variable Message Signs. *Better Roads*, v 57, n 3, 1987, pp. 24-25.
3	With the current developments and enthusiasm for the intelligent Vehicle Highway System (IVHS) for the increased operational improvement of our congested highway systems, research is required for identifying and developing the safety improvements that can be obtained from these systems. Current research and development is underway to do just that. This paper will provide a review of the safety-related research of the advanced technology being conducted in the United States of America and how it is being applied to improve highway safety.	H. H. Bissell. How Will Advanced Technology Be Applied for Highway Safety? *ITE 1993 Compendium of Technical Papers*, 1993, pp. 362 -
3	This paper presents the design, implementation, and partial evaluation work performed by a European consortium for the development of a Variable Message Sign (VMS) information and guidance system in the city of Aalborg, Denmark. The employed control strategy is based on simple automatic control concepts with decentralized feedback loops aiming at approximating a user optimal traffic flow distribution in the mixed network, that comprises a motorway axis and an urban component. Simulation studies demonstrate the potential improvements achievable with this kind of control measures and control strategies. The implementation concept and first field results are outlined.	S. Mammar, A. Messmer, P. Jensen, M. Papageorgiou, H. Haj-Salem, and L. Jensen. Automatic Control of Variable Message Signs in Aalborq. *Transportation Research Part C: Emerging Technology*, v 4, n 3, June 1996, pp. 131-150.
3	This is a summary of an Equipment Standard of the Institute of Transportation Engineers approved in September 1993. It supersedes the Proposed Standard dated April 1988.This Equipment Standard was developed and approved in accordance with formally adopted Institute procedures designed to help assure that all interested parties are given opportunities to provide input. All input received has been considered such that the report would represent the best consensus on the state of the art at the time of approval. Any requests for revisions must be submitted to the Director of Technical Programs, Institute of Transportation Engineers, 525 School St., S.W., Suite 410, Washington, DC 20024. Such requests shall contain a statement of concern, appropriate material to support the concern and other relevant information. This standard was developed by ITE Technical Council Committee 7S-3, Work Zone Traffic Control Standards Changeable Message Signs. The committee's initial scope was to develop a performance standard for portable bulb-type changeable message signs. The committee also is in the process of developing a proposed standard for flip-disk changeable message signs. ITE supports other changeable message sign technologies and will develop standards for those as appropriate.	*An Equipment Standard: Portable Bulb-Type Changeable Message Signs for Highway Work Zones.* ITE Technical Council Committee 7S-3. ITE Journal, April 1994, p. 26.

Category	Abstract	Reference
4	Incident-induced congestion is a major source of delay and frustration for drivers in large urban areas. Advanced Traveler Information Systems (ATIS) have been proposed within the framework of Intelligent Vehicle Highway Systems (IVHS) to address one component of the incident-induced congestion problem: diversion of drivers to alternate routes. To fully utilize the potential of ATIS, transportation managers need to understand driver response to such congestion. This study examines short-term commuter response to unexpected (incident-induced) congestion. It investigates factors which influence diversion from the regular route and return to the regular route after diversion. Discrete choice models of diversion and return behavior show that the following information and trip factors increase the probability of diversion: delay information received from radio traffic reports as opposed to observation of congestion, longer delays and longer travel times, and number of alternate routes used in the past. Further, drivers were more likely to divert if they lived in the city as opposed to the suburbs, were risk seekers, had a higher stated propensity to divert and were male. However, anticipated congestion on the alternate route inhibited drivers from diverting. Finally, drivers who had longer commute trips were more likely to return to their regular route. The most important implication for designing ATIS is that traffic information must be "customized" to account for individual differences. Specific design implications are discussed in the paper.	A. Khattak, J. Schofer, and F. Koppelman. Commuters' En route Diversion and Return Decisions: Analysis and Implications for Advanced Traveler Information Systems. *Transportation Research Part A*, v27, n2, 1993, pp. 101-111.
4	*The* on-line application of nonlinear optimization methods to feedback control of motorway networks is presented. The considered control measure is route diversion via Variable Message Signs (VMS). The control task is formulated as a dynamic, nonlinear, discrete-time optimal control problem with constrained control variables and is solved by gradient based search. An algorithm for the heuristic search of optimal discrete (binary) control sequences is also presented. Feedback control is realized by solving the optimization problem for each control interval over a sufficiently long future time horizon (certainty equivalent open-loop feedback control). As a prerequisite, a state-space description of the network traffic dynamics is derived from a macroscopic model that is also used in the simulation program METANET. Simulation results for route diversion on a hypothetical example network are provided. The required computational effort is assessed and the control benefits are evaluated in terms of global network performance, switching frequency of VMS and user optimality.	A. Messmer and M. Papageorgiou . Route Diversion Control in Motorway Networks via Nonlinear Optimization. IEEE Transactions on Control Systems Technology, v3, nl, March 1995, pp. 144-154.
4	In this thesis we propose three hypotheses regarding drivers' behavior in the presence of information. The simultaneous hypothesis assumes that drivers incorporate all the factors that affect their decision simultaneously (including traffic information). The two stage hypothesis assumes that drivers first update their perceptions based on the new information that they have acquired or experienced, and subsequently make route choice decisions based on their updated perceptions. Finally, the default hypothesis assumes that there is an underlying behavioral pattern for each driver which serves as default behavior if no unusual or unexpected conditions occur. Information on unexpected conditions triggers reevaluation of the default behavior. The two main elements required to implement the above hypotheses are models of drivers perceptions, and models of the decision process itself. We present a framework for modeling both perceptions and the route choice process in the presence of information using concepts from fuzzy sets theory, approximate reasoning, and fuzzy control. The first approach is based on the classical discrete choice paradigm appropriately extended to incorporate fuzzy attributes in the systematic utility component. The maximum likelihood function of the fuzzy utility model is formulated and used forthe calibration of its parameters. The second approach is based on concepts from approximate reasoning and fuzzy control. Linguistic rules of the form: "IF ..THEN . are used. The rules describe attitudes towards taking a specific route given (possibly vague) perceptions on network attributes. They are used as anchoring schemes for decisions, while the adjustments of the rules to changing conditions is done by an approximate reasoning mechanism. The use of the fuzzy, approximate reasoning methodology facilitates a flexible rule interpretation by automatically deriving rules that are close to the original rules. We conclude by presenting results from a case study. Preliminary results support our hypothesis that route choice behavior in the presence of information can be modeled by a small set of intuitive and reasonable rules. The results also compare favorably to results obtained by more traditional approaches.	T. Lotan. Modeling Route Choice Behavior in the Presence of Information Using Concepts from Fuzzy Set Theory and Approximate Reasoning. *Transportation Research Part A*, v 29, n 1, 1992, p. 61.

Category	Abstract	Reference
4	In this paper we analysis the impact of both radio traffic information and variable message sign information on route choice behavior. The empirical analysis is based on an extensive survey held among road users in the Amsterdam corridor in July 1994. The data is stemming from the EC DRIVE II project BATT. To analysis the factors that influence route choice behavior, several types of discrete choice models (ordered probit, multiple logit and bivariate ordered probit) have been estimated. Bivariate models are needed to model the (endogenous) dependency of the use of radio traffic information and variable message sign information. The results confirm earlier findings that women are less likely to be influenced by traffic information. New is the finding that commuters are less likely to be influenced, and that the level of satisfaction with alternative routes is strongly related to the type and distance of the alternative road. The analysis also reveals that the impacts of radio traffic information and variable message sign information on route choice behavior are very similar, and that route choice adaptations based on radio traffic information are positively related to route choice adaptations based on variable message sign information. An interesting issue is the willingness-to-pay for having in-vehicle dynamic traffic information. As expected, the willingness-to-pay is relatively large for male drivers on business trips. Another important new finding is that the results suggest that there is a positive correlation between the use of radio traffic information and Variable message sign information.	R. H. M. Emmerick, P. Nijkamp, P. Rietveld, and J. N. Van Ommeren. Variable Message Signs and Radio Traffic Information: An Integrated Empirical Analysis of Drivers' Route Choice Behavior. *Transportation Research Part A*, v 30, n 2, 1996, pp. 135-153.
4	Increasing urban and suburban traffic congestion has motivated interest in Advanced Traveler Information Systems (ATIS) aimed at improving the performance of transportation networks and the quality of travel. To contribute to the development of ATIS systems, this research seeks to present a new generation of dynamic network equilibrium models, including traveler's mode choice, departure/arrival time choice and route choice. The instantaneous dynamic user-optimal (DUO) route choice problem is to determine vehicle flows at each instant of time on each link resulting from drivers using instantaneous minimal-time routes. Two instantaneous DUO route choice models are formulated using the optimal control theory approach. A discrete time nonlinear programming program of the DUO route choice model is solved by the Frank-Wolfe technique embedded in the diagonalization procedure. The formulation of the ideal DUO route choice problem is based on the underlying choice criterion that each traveler uses the route that minimizes his/her future (actual) travel time when departing from the origin to his/her destination. Both route-based and link-based optimal control programs of ideal DUO route choice problems are presented. Then, a link-based variational inequality problem is formulated. For a comparison, a set of dynamic system-optimal route choice models are also formulated. Dynamic stochastic user optimal (DSUO) route choice models are stochastic extensions of our deterministic DUO route choice models by assuming certain distributions of travelers' perceived travel times. Two logit-type models are formulated for the instantaneous DSUO and ideal DSUO route choice problems. Then, the diagonalization technique and DYNASTOCH algorithms are used to solve the two models. A joint dynamic departure time/route choice problem is to determine travelers' departure times and choose their best routes at each instant of time. We present a bilevel programming formulation for this problem. Then, a two-stage non-hierarchical programming formulation is proposed for a general combined DUO mode/departure time/route choice problem with multi-class travelers. In order to implement the above dynamic models in realistic urban transportation networks, two sets of time-dependent travel time functions for signalized arterial network links are recommended.	B. Ran. Dynamic Transportation Network Models for Advanced Traveler Information Systems. *Transportation Research Part A*, v 29, n 1, 1993, p. 60.
4	Intelligent Transportation Systems (ITS) can reduce traffic congestion by displaying congestion-related delay information on roadside variable message signs or in-vehicle displays. Message format and content may have a significant impact on the percentage of drivers who decide to make a route diversion. In this study, the effect of various traffic information message types on driver routing decisions was evaluated. Results suggest that messages including both an advisory and a descriptive component promote situation awareness and rapid decision making, both of which are critical for this application.	W. B. Fain. *Analysis of the Influence of Traffic Information Messages on Route Selection,* Proceedings of the Human Factors and Ergonomics Society, v 2, Human Factors and Ergonomics Society, Inc., Santa Monica, CA, 1995, pp. 1082-1086.

Category	Abstract	Reference
4	Models for route choice in the presence of information and motorist reaction to route guidance are currently under development. A major difficulty in developing such models is the lack of appropriate data for testing and calibration. This paper describes a PC-based driving simulator that can be used for collecting relevant data in a controlled environment. The simulator uses 2-D graphics, and consists of three main modules: network performance, guidance generation, and user interface. A flexible design permits the simulation of a wide variety of information systems on any network. The functionality of the driving simulator is demonstrated in a case study with data collected from a group of 10 subjects. The data was used to calibrate a new class of route choice models in the presence of information, which are based on concepts from fuzzy sets and approximate reasoning. The results indicate that until data collected on actual route choice behavior in the presence of information becomes available, appropriately designed driving simulators can become useful tools.	H. N. Koutsopoulos, T. Lotan, and Q. Yang. A Driving Simulator and its Application for Modeling Route Choice in the Presence of Information. *Transportation Research Part C*, v 2, n 2, 1994, pp. 91-107.
4	This paper proposes a theoretical methodology and practical data collection approach for modeling en route driver behavioral choice under Advanced Traveler Information Systems (ATIS). The theoretical framework is based on conflict assessment and resolution theories popularized in psychology and applied to models of individual consumer behavior. It is posed that en route assessment and adjustment is a reactionary process influenced by increased conflict arousal and motivation to change. When conflict rises to a level at which conflict exceeds a personal threshold of tolerance, drivers are likely to alter en route behavior to alleviate conflict through either route diversion of goal revision. Assessment and response to conflict arousal directly relate to the driver's abilities to perceive and predict network conditions in conjunction with familiarity of network configurations and accessible alternate routes. Data collection is accomplished through FASTCARS (Freeway and Arterial Street Traffic Conflict Arousal and Resolution Simulator), in interactive microcomputer-based driving simulator. Limited real-world implementation of ATIS has made it difficult to study or predict individual driver reaction to these technologies. It is contended here that in-laboratory experimentation with interactive route choice simulators can substitute for the lack of real-world applications and provide an alternate approach to data collection and driver behavior analysis. This paper will explain how FASTCARS is useful for collecting data and testing theories of driver behavior.	J. L. Adler, W. W. Recker, and M. G. McNally. A Conflict Model and Interactive Simulator (FASTCARS) for Predicting En route Driver Behavior in Response to Real-Time Traffic Condition Information. *Transportation*, v 20, 1993, pp. 83-106.
4	This paper investigates the reliability of information on prevailing trip times on the links of a network as a basis for route choice decisions by individual drivers. It considers a type of information strategy in which no attempt is made by some central controller or coordinating entity to predict what the travel times on each link would be by the time it is reached by a driver that is presently at a given location. A specially modified model combining traffic simulation and path assignment capabilities is used to analyze the reliability of the real-time information supplied to the drivers. This is accomplished by comparing the supplied travel times (at the link and path levels) to the actual trip times experienced in the network after the information has been given. In addition, the quality of the decisions made by drivers on the basis of this information (under alternative path switching rules) is evaluated ex-post by comparing the actually experienced travel time (given the decision made) to the time that the driver would have experienced without the real-time information. Results of a series of simulation experiments under recurrent congestion conditions are discussed, illustrating the interactions between information reliability and user response.	H. S. Mahmassani and P. Shen-Te Chen. An Investigation of the Reliability of Real-Time Information for Route Choice Decisions in a Congested Traffic System. *Transportation*, v 20, pp. 157 - 178.
4	Understanding traveler response to potential ATIS services is critical for designing such services and evaluating their effectiveness. Extensive data is required for developing the models necessary to provide this understanding. In this paper we examine one source of such data: traveler simulators. We make a distinction between travel simulators, used to study the travelers response to information acquisition, and driving simulators, which are elaborate tools used mainly for human factors research. Traveler simulators have the potential to provide a wealth of data collected relatively inexpensively under controlled conditions. However the data may suffer from biases introduced because of the laboratory nature of travel simulators. We examine various existing simulators and comment on their advantages and disadvantages. We make recommendations for simulator design characteristics that increase the reliability of the data collected and suggest enhancements so that current simulators can be used for the collection of data related to access and acquisition of ATIS products as well. We conclude the paper with recommendations for future research in the area.	H. N. Koutsopoulos, A. Polydoropoulou, and M. Ben-Akiva. Travel Simulators for Data Collection on Driver Behavior in the Presence of Information. *Transportation Research Part C*, v 3, n 3, 1995, pp. 143-159.

Category	Abstract	Reference
4	Decisions about implementing Advanced Traveler Information Systems (ATIS) should be based on the individual and social benefits expected from such technologies, which will be strongly dependent on the ways travelers respond to these new information sources. This paper explores the behavioral issues important to understanding traveler reactions to ATIS; it discusses evaluation strategies, including stated preference methods and observation of revealed behavior in laboratory simulations and fieldtests with various degrees of control and complexity. Advantages and disadvantages of different approaches are reviewed, and the experimental design challenges of site selection, recruitment of test subjects, and measurement of behavior are explored.	J. L. Schofer, A. Khattak, and F. S. Koppelman. Behavioral Issues in the Design and Evaluation of Advanced Traveler Information Systems. *Transportation Research Part C*, v 1, n 2, 1993, pp. 107-117.
4	This paper aid to gain more insight into the implications of information provision to drivers on the performance of road transport networks with recurrent congestion. For this purpose, a simulation program consisting of three components has been written. The first component is the traffic simulation model, the second component is the information provision mechanism, and the third component monitors the behavioral decision-making process of the drivers which is modeled using a utility-based satisfying principle. Three types of information provision mechanisms will be considered: information based upon own-experience, after-trip information and real-time en route information. The findings in this paper, obtained in a hypothetical context, underline the important relationship between overreaction, the level of market penetration and the quality of the information. High quality information allows a high level of market penetration, while low quality information, even when provided at low levels of market penetration, induced overreaction. Furthermore, realtime en route information is in particular beneficial during the process leading to a steady state; it reduces the variance in travel time considerably. The paper concludes with a discussion on the market potential of motorist information systems when commercially marketed.	R. H. M. Emmerick, K. W. Axhausen, P. Nijkamp, and P. Rietveld. Effects of Information in Road Transport Networks with Recurrent Congestion. *Transportation*, v 22, n 1, Feb. 1995, pp. 21-53.
4	One of the benefits of advanced traveler information systems (ATISS) is their ability to divert travelers to alternative routes during traffic incidents to alleviate congestion. ATISs may effectively convince travelers to divert to alternative routes by providing information that is considered useful. Therefore, it is important to identify the factors that explain drivers' route diversion behaviors to properly assist in the design and implementation of ATISS. An application of latent variable models to determine the factors that affect drivers' stated intentions to divert from their usual routes when faced with traffic congestion is described. Two latent variables were identified: drivers' attitudes toward route diversion and their perceptions of the reliability of information provided by radio traffic reports (RTRS) or changeable message signs*(CMSs)*. These two latent variables were determined to be significant explanatory variables of route diversion intentions. Some drivers' travel and socioeconomic characteristics and the type of information provided by RTRs and*CMSs* were also found to be important explanatory variables.	S.M. Madanat, C. V. D. Yang, and Y. Yen. Analysis of Stated Route Diversion Intentions Under Advance Traveler Information Systems Using Latent Variable Modeling. *Transportation Research Record 1485*, TRB, National Research Council, Washington, D.C., July 1995, pp. 10-17.
4	This paper studies the effects of traffic information on Seattle-area commuters. Models of commuters' route-change frequency, the duration of traffic delay needed to induce a route change, and the influence of pre-trip traffic information on departure-time choice, mode choice, and route choice are estimated. Two modeling techniques are used in these estimations: an ordered logit probability approach and a Weibull duration model with a heterogeneity correction term. The findings of these model estimations provide important insights into how traveler information systems should be designed, implemented, and marketed.	F. Mannering, S. Kim, W. Barfield, and L. Ng. Statistical Analysis of Commuters' Route, Mode, and Departure Time Flexibility. *Transportation Research Part C*, v 2, n 1, 1994, pp. 35-47.
4	This study intends to examine the way dynamic traffic information should be provided by observing driver response to travel time information. It aims to examine driver response to a travel time information system actually in operation, A panel survey has been conducted in order to reveal the effects of travel time information on drivers' travel behavior. Six waves of surveys were scheduled between April 1991 and September 1993. The information system surveyed provides drivers with real time information of predicted travel times on three alternative routes by NIM (variable message sign) on road. This paper elucidates the basic thinking behind and implementation of the surveys and outlines the results of preliminary analyses of data. Route choice models based on individual response to traffic information are also estimated.	T. Uchida, Y. Iida, and M. Nakahara. *Panel Survey on Drivers' Route Choice Behavior Under Travel Time Information*. Vehicle Navigation and Information Systems Conference 1994, IEEE, Piscataway, NJ, 1994, pp. 383-388.

Category	Abstract	Reference
5	This paper considers information systems in public transit in which the passenger receives information in *real time* regarding projected vehicle travel times. Such information systems may have value to passengers in situations where they may choose among different origin-to-destination paths. To provide a preliminary assessment of these systems, an analytic framework is presented to evaluate path choices and travel time benefits resulting from real-time information. A behavioral model of transit path choice is presented that frames the choice in terms of a decision whether to board a departing vehicle. Furthermore, this path choice model accommodates network travel times that are both stochastic and time-dependent, two elements that have been neglected in previous studies but are critical to evaluating real-time information systems. The path choice model is extended to demonstrate how real-time information may be incorporated by the passenger in making a path choice decision. This analytic framework is applied to a case study corridor at the Massachusetts Bay Transportation Authority (MBTA), using a computer simulation to model vehicle movements and passenger path choices in the corridor. The results suggest that realtime information yields only very modest improvements in passenger service measures such as the origin-to-destination travel times and the variability of trip times. Based on this analysis, the quantitative benefits of real-time information for transit passenger path choices appear to be questionable.	M. D. Hickman and N. H. M. Wilson. Passenger Travel Time and Path Choice Implications of Real-Time Transit Information, *Transportation Research Part C*, v 3, n 4, 1995, pp. 211-226.
5	Studies have shown that most drivers do not slow down in response to the standard regulatory or advisory speed si-ns that are customarily used to regulate speeds at temporary traffic control zones (work zones). This study evaluated the effectiveness of the Changeable Message Sign (CMS) with a radar unit inreducing speeds at work zones. Four CMS messages designed to warn drivers that their speed exceeded the maximum safe speed were tested at seven work zones on two interstate highways in Virginia. Speed and volume data for the whole population traveling through the sites were collected with automatic traffic counters. To assess the effect of the CMS with radar (on high-speed drivers in particular), vehicles that were traveling above a selected threshold speed triggered the radar-activated display and were videotaped as they passed through the work zones. The data obtained from the videotapes were used to@obtain speed characteristics of these speeding drivers as they traversed these Study sites. Statistical tests were then conducted using these speed characteristics to determine whether significant reduction in speed accompanied the use of CMS. The results indicate that the CMS with radar significantly reduced the speeds of speeding drivers. The messages used were rated according to their level of effectiveness in the following order: (1) YOU ARE SPEEDING SLOW DOWN. (2) HIGH SPEED SLOW DOWN, (3) REDUCE SPEED IN WORK ZONE, and (4) EXCESSIVE SPEED SLOW DOWN.	N. J. Garber and S. T. Patel. Control of Vehicle Speeds in Temporary Traffic Control Zones (Work Zones) Using Changeable Message Signs with Radar. *Transportation Research Record 1509*, TRB, National Research Council, Washington, D.C., 1995, pp. 73-81.
5	Drivers may change their speeds at different locations within a work zone in response to roadway geometry and traffic control devices. Speeds of vehicles at different locations within a work zone were determined in this study in order to plot their speed reduction profiles. Vehicles were followed from the time they entered a 1.5-mi-long study section until they exited from it. Automobiles and trucks showed similar speed-reduction patterns. Four categories of drivers were identified on the basis of these patterns. About 63 percent of drivers reduced their speeds considerably after passing the first work zone speed-limit signs 'Category 1). Nearly II percent of drivers reduced their speeds hen they neared the location of construction activities (Category 2). About II percent of all drivers did not reduce their high speeds (Category 3). The remaining drivers did not indicate a distinct pattern (Category 4). Three distinct speed-reduction patterns were observed for the drivers in Category 1. The first group decreased their speeds near the first speed-limit signs and had further speed reductions at the work space. The second group drove similarly to the first group, but increased their speed between the two points. The third group reduced their speed near the first speed limit signs and kept that speed until they passed the work space. The average speed decreased as the vehicles approached the work space, but rapidly increased after passing it. Even at the work space, about 2/3 of automobile drivers and more than half of truck drivers exceeded the speed limit.	R. F. Benekohal, L. Wang, R. Orloski, and L. M. Kastel. Speed-Reduction Patterns of Vehicles in a Highway Construction Zone. *Transportation Research Record 1352*, TRB, National Research Council, Washington, D.C., 1992, pp. 35-45.

Category	Abstract	Reference
5	Nine field studies were conducted on four-lane divided highways In Texas and Oklahoma to evaluate two alternative traffic control approaches: single-lane closure In one direction versus a crossover with two-lane, two-way traffic operations (TLTWO). The variables studied were: worker productivity, job duration, construction costs, traffic control device costs, highway-user costs, accidents, conflicts, and capacity. Worker productivity was measured Indirectly from job duration and construction costs. Because of limited data, it was not possible to Identify the conditions under which one traffic control alternative offers costs savings over the other. Highway-user costs for each study site were calculated using a modified version of a work-zone queue and user-costs evaluation model. Graphs and tables show the relationships between hourly traffic volumes and road-user costs for the sites studied.	C. Dudek, S. Richards, and J. Buffington. Some Effects of Traffic Control on Four-Lane Divided Highways. *Transportation Research Record 1086*, TRB, National Research Council, Washington, D.C., 1986, pp. 20-30.
5	Constructibility, in simple words, is the ability to construct effectively. This study involved the development of a prototype system to perform highway constructibility analysis of traffic-control planning (TCP). The results of meetings with personnel at the Texas Department of Transportation (TXDOT) indicated that work-zone traffic control is one of the most critical factors impeding the constructibility of highway projects. The lack of personnel, the inability to fill the knowledge void caused by transfer or retirement of experts in the field, and the inability to effectively learn from mistakes are some factors that indicate a need for advanced automation techniques in the highway construction industry. The prototype system developed included a database module (CONTRAF), an expert system module (TRAPS), and a fuzzy scheduling module. It is developed to provide designers and construction managers with generic constructibility recommendations on traffic control, and direct access to a constructibility database, before the final TCP 4 s designed. Once the final TCP is developed, the system helps in phasing the activities, calculating the fuzzy durations of the activities, and linking the activities to a project-management software for project scheduling.	D. J. Fisher and R. Naveen. Automated Constructibility Analysis of Work-Zone Traffic-Control Planning. *Journal of Construction Engineering and Management*, v 122, n 1, 1996, pp. 36-43.
6	Between 1979 and 1981, the need for repair work on Houston area freeways (particularly those over twenty years old or carrying traffic volumes near or over 200,000 vehicles per day) increased markedly. Complaints from the traveling public about traffic congestion caused by such work led to one legislative suggestion (not passed) that all freeway work in the Houston area be limited to night operations. Although no legislation was passed, a result of the above sentiment was that work zone operations were generally restricted to night-time hours and weekends. It is during these time periods that speeds are high and the chances for errant behavior increase. Unfortunately, these concerns became fact at an alarming frequency. In 1980 and 1981, 12 highway workers were killed and 34 injured while working on Houston's freeways. Most of these casualties were caused by drunk drivers and speeding motorists.	S. Z. Levine. Real Time Traffic Control of Urban Freeway Work Zone Operations.
6	Traffic monitoring and detection systems are important for constructing closed-loop traffic-signal control, freeway-control, and congestion-management systems. Most detection and monitoring systems depend on inductive loops. Recently, many agencies have been investigating video-image-based detection systems because cameras can collect data on several traffic lanes and can be installed quite rapidly on an adjacent pole or bridge. User consensus is that the basic hardware architecture of these systems is well defined. However, there is room for significant improvements in performance and capability of video-detection algorithms. Several researchers are currently working to develop new algorithms. However, due to technology limitations these algorithms have traditionally been evaluated at a macroscopic level by comparing counts obtained by loop detectors with the image-based detection system. This paper discusses the development of a multimedia database-management system for investigating the microscopic performance of video-detection algorithms. The paper describes the process of acquiring the proper data, a definition for a suitable database schema, and the peripheral database clients required to evaluate detection algorithms.	D. Bullock and S. Mantri. Multimedia Data Model for Video-Direction Research. *Journal of Transportation Engineering*, v 121, n 5, September/October 1995, pp. 385-390.

Category	Abstract	Reference
6	The generation and dissemination of driver guidance that can be used for real-time diversion of traffic are expected to be implemented through the use of real-time traveler information systems. To implement these functions, a system structure consisting of a surveillance module, a congestion prediction module, and a control and routing (CAR) module is proposed, with the focus on the approaches that may be used for congestion prediction and the strategies that may form the basis for routing. It is argued that a congestion prediction capability is critical for the effectiveness of an on-line traveler information system. Such a capability is required to accurately forecast traffic conditions that may exist in the near future. The use of a dynamic traffic assignment model for congestion prediction is suggested. Such a model consists of dynamic driver behavior and network performance modules as well as origin-destination updating capability. Alternatively, statistical time-series methods may be necessary to generate predictions of future traffic conditions. The advantages and difficulties of adopting either approach are discussed. The predicted congestion information is passed to the CAR module to develop diversion strategies to alleviate both recurring and nonrecurring congestion. The role of routing strategies and update frequency in determining guidance effectiveness is discussed.	I. Kaysi, M. Ben-Akiva, and H. Koutsopoulos. Integrated Approach to Vehicle Routing and Congestion Prediction for Real-Time Driver Guidance, Transportation Research Record 1408, TRB, National Research Council, Washington, D.C., 1993, pp. 66-74.
6	The Texas Department of Transportation has undertaken a task to keep San Antonio district's freeway and main arteries congestion-free by implementing an advanced traffic management system (ATMS). The ATMS computer is responsible for the detection, routing, analysis, display, storage and archiving of the incident data. A video surveillance system provides incident verification and a way to determine required emergency response. The ATMS monitors the status and provides control of the field equipment, and controls the configuration of all digital communications network equipment. The software supporting this program is an integration of commercial-off-the-shelf products and custom code. The software analyzes speed, volume and occupancy data.	V. P. Pearce, B.G. Keeler, and J. A. Schmid. San Antonio ATMS: Innovation Tackles the Congestion Challenge. *ITE Journal*, v 64, n 6, June 1994, pp. 23-27.
6	Sources of bias and variability in the measurement of time-based traffic eventsby using video recording-and-playback systems are described. Bias can affect accuracy, whereas the lack of precision can increase the minimum sample size. Equations are described that can be used to estimate the adjustment needed to remove bias front the recorded data and to estimate the standard deviation of the measurement process. The equations are sensitive to the method of extracting the individual traffic event times from the videotape. These methods include manual extraction, which uses a frame-by-frame analysis, and automated extraction, which uses a video imaging system to analyze the tape during playback at normal speed. The manual method is found to yield less bias and lower variability than the automated method.	J. A. Bonneson and J. W. Fitts. Traffic Data Collection Using Video-Based Systems. *Transportation Research Record 1477*, TRB, National Research Council, Washington, D.C., 1995, pp. 31-40.
6	Travel time information is becoming more important for applications ranging from congestion measurement to real-time travel information. This paper contains a discussion of several advanced techniques for travel time data collection, including electronic distance-measuring instruments, computerized and video license plate matching, cellular phone tracking, automatic vehicle identification, automatic vehicle location, and video imaging. The various advanced techniques are described, the necessary equipment and procedures outlined, the applications of each technique are discussed, and the advantages and disadvantages are summarized.	S. M. Turner. *Advanced Techniques for Travel Time Data Collection.* Vehicle Navigation and Information Systems Conference 1995, IEEE, Piscataway, NJ, 1995, pp. 40-47.
6	Many data-collection methods are available from simple manual methods to advanced automatic image processing techniques. For many practical purposes video recording has become a widely used tool. Though this method is simple and is extensively used, accuracy in estimating actual speed and associated measurement errors have not been quantitatively examined. This paper investigates the mathematical properties of measurement error in vehicular speed data reduced from video images. Primary focus was on the measurement-error probability function, which incorporates the effects of the embedded video camera time-base resolution, fiducial mark interval, and actual vehicle speed. Mathematical derivations of the probability density function (PDF) are presented, and a Monte Carlo simulation technique was applied verifying the mathematically derived probability function. Both graphical comparisons and goodness-of-fit tests demonstrated very good agreement. The probability function presented in this paper provides a very useful tool because it allows traffic engineers to quantify in advance the probability of occurrence of certain measurement-error magnitudes and to adjust the data-collection plan accordingly.	C. Kou and R.B. Machemehl. Probabilistic Speed-Estimation Measurement Errors Through Video Images. Journal of Transportation Engineers, v 123, n 2, March/April 1997, pp. 136 - 141.

APPENDIX B

Meeting Notes of Brainstorming Session on December 18, 1997

Nebraska Department of Roads
Research Project SPR-PL-1(35)P513
Alternative Driver Information to Alleviate Work Zone-Related Delays

Brainstorming Session
December 18, 1998

Meeting Notes

A brainstorming session for the Nebraska Department of Roads (NDOR) Research Project SPR-PL-1(35)P513, *Alternative Driver Information to Alleviate Work Zone-Related Delays*, was held in the NDOR Auditorium at 2:00 pm on Thursday, December 18, 1998. The following individuals participated in the session:

Captain A. K. Anderson, Troop Commander, Nebraska State Patrol, 471-4680
Jim Gould, Vice President, Trafcon, 434-1776
Joe Mack, Director Safety, Werner Enterprises, 895-6640
Gene Pohl, Safety Supervisor, Werner Enterprises, 895-6640
Frank Doland, Research Engineer, Federal Highway Administration, 437-5963
Matt Redington, Highway Engineer Trainee, Federal Highway Administration, 437-5976
Kyle Hall, Project Manager, District 1, NDOR, 471-0850
Paul Koefoot, Project Manager, District 1, NDOR, 471-0850
Dalyce Ronnau, Assistant Maintenance Engineer, Maintenance Division, NDOR, 479-4544
Dan Waddle, Signing Engineer, Traffic Engineering Division, NDOR, 479-4594
Montasir Abbas, Graduate Research Assistant, Civil Engineering, UNL, 472-1102
Dan Jessen, Undergraduate Research Assistant, Civil Engineering, UNL, 472-1102
Pat McCoy, Professor, Civil Engineering, UNL, 472-5019
Dalyce Ronnau was the session facilitator. Montasir Abbas and Dan Jessen were the recorders.

The following session agenda was completed.

1. **Setting the Stage:** The problem to be addressed by the brainstorming session was presented. Pat McCoy explained that the brainstorming session was being held as part of the NDOR Research Project SPR-PL-1(35)P513, *Alternative Driver Information to Alleviate Work Zone-Related Delays*. The purpose of the project is to find better ways to control traffic through work zones on rural interstate highways, primarily ways to: (1) improve the safety and efficiency of merging operations in advance of lane closures and (2) reduce the speed of traffic in work zones. He indicated that the brainstorming session is an effort to generate some new ideas from different perspectives for consideration in the research.

   Dan Waddle used a model to describe the traffic control plan currently used by NDOR at lane closures on rural interstate highways.

2. **Experiences/Problems Related to Interstate Lane Closures:** Dalyce Ronnau asked the participants to describe their experiences and observations related to problems associated wth lane closures on rural interstate highways. The following problems were identified:

   - speed of traffic too high
   - drivers ignoring the lane transition sign
   - slow paddle operations in work zones confusing
   - traffic congestion at the taper
   - aggressive drivers
   - drivers not yielding to traffic in the closed lane
   - accordion effect (shock waves)
   - drivers having difficulty judging gap sizes
   - credibility of signing (lanes not always closed when signs say they are)
   - long queues during congestion making it difficult for drivers to tell which lane is closed
   - unnecessarily long work zones (much longer than length of actual construction work)
   - ignorant drivers
   - lack of enforcement
   - inadequate space for enforcement in work zones (stopping violators is difficult)
   - difficulty of speed and headway enforcement during high volumes
   - two work zones too close together
   - length of merging area too short for trucks
   - left-to-right merge very difficult for trucks
   - difficulty and danger associated with replacing traffic control devices
   - gawkers (drivers slowing to see what going on in the work zone)
   - lanes too narrow for trucks (especially double bottoms in cross winds)

3. **Possible Improvements:** Dalyce Ronnau asked the participants to suggest ways to solve the problems identified. The following possible improvements were suggested:

   - longer and smoother speed zone transition (75 mph→65 mph @ 2 mi→55 mph @ taper)
   - dummy radar
   - longer taper
   - changeable message sign (CMS) displaying traffic speeds
   - CMS displaying courteous driver messages (be nice let drivers in)
   - 2nd arrow board at 1 mile in advance
   - trucks controlling traffic (trucks traveling side-by-side to block closed lane)
   - smooth transition
   - advance CMS/highway advisory radio (HAR) advising drivers of congestion
   - advance CMS/HAR advising drivers alternate routes
   - news media advising of alternate routes
   - advance CMS messages (watch for slow and stopped traffic)
   - longer lower speed zone
   - work zone traveler information at rest areas and fuel stops
   - work zone call-in line
   - work zone information on DTN monitors

- truck driver advisories on Comdata Network
- work zone advisories on CB radio
- state patrol escorts during congestion
- control volume (close or meter entrance ramps)
- merge arrows on pavement in closed lane
- rumble strips in closed lane
- advise drivers to maintain speed
- no passing lines in closed lane
- hash marks across pavement in closed lane
- move left/right lines in closed lane
- work zone advisories on CMS in advance of upstream interchange
- CMS messages based on input from traffic detection system
- more CMSs
- use news media to educate drivers/public information campaign
- speed limit signs with flashing beacons
- elimination of the use of slow paddles
- narrow lanes to move traffic left/right
- always close left lane
- Iowa weave
- Indiana no passing zone
- screen driver's view of work area
- keep equipment maintained
- pamphlets on courteous driving in work zones
- law enforcement at every work zone
- maintain credibility of signing

4. **Best Options:** Dalyce Ronnau asked the participants to select the most promising improvements suggested. The following improvements were identified as the best options:

- longer and smoother speed zone transition (75 mph→65 mph @ 2 mi→55 mph @ taper)
- maintain credibility of signing
- Indiana no passing zone
- always close left lane
- use news media to educate drivers/public information campaign
- work zone traveler information at rest areas and fuel stops (DTN monitors)
- CMS displaying courteous driver messages (be nice let drivers in)
- no passing lines in closed lane
- combination of hash marks, move left/right lines, merge arrows, rumbles strips, DO NOT PASS signs, narrower lane width in closed lane approximately 1 mile in advance
- CMSs in advance
- CMS displaying traffic speeds

5. **Wrap Up:** Pat McCoy explained that the ideas obtained from the brainstorming session will be used by the study team to develop alternative traffic control strategies. Two of the alternatives will be selected by NDOR for evaluation in the field next summer. It was suggested that others may also have ideas to offer about ways to control traffic speeds and merging at lane closures on rural interstate highways. It was agreed that: (1) Jim Gould will contact ATSSA for information on any innovative methods; (2) Captain Anderson will investigate the possibility of surveying the highway patrols in other states for ideas; and (3) Pat McCoy will contact Duane Henn of Werner Enterprises regarding the possibility of conducting a survey to identify the best methods observed by Werner Enterprises truck drivers.