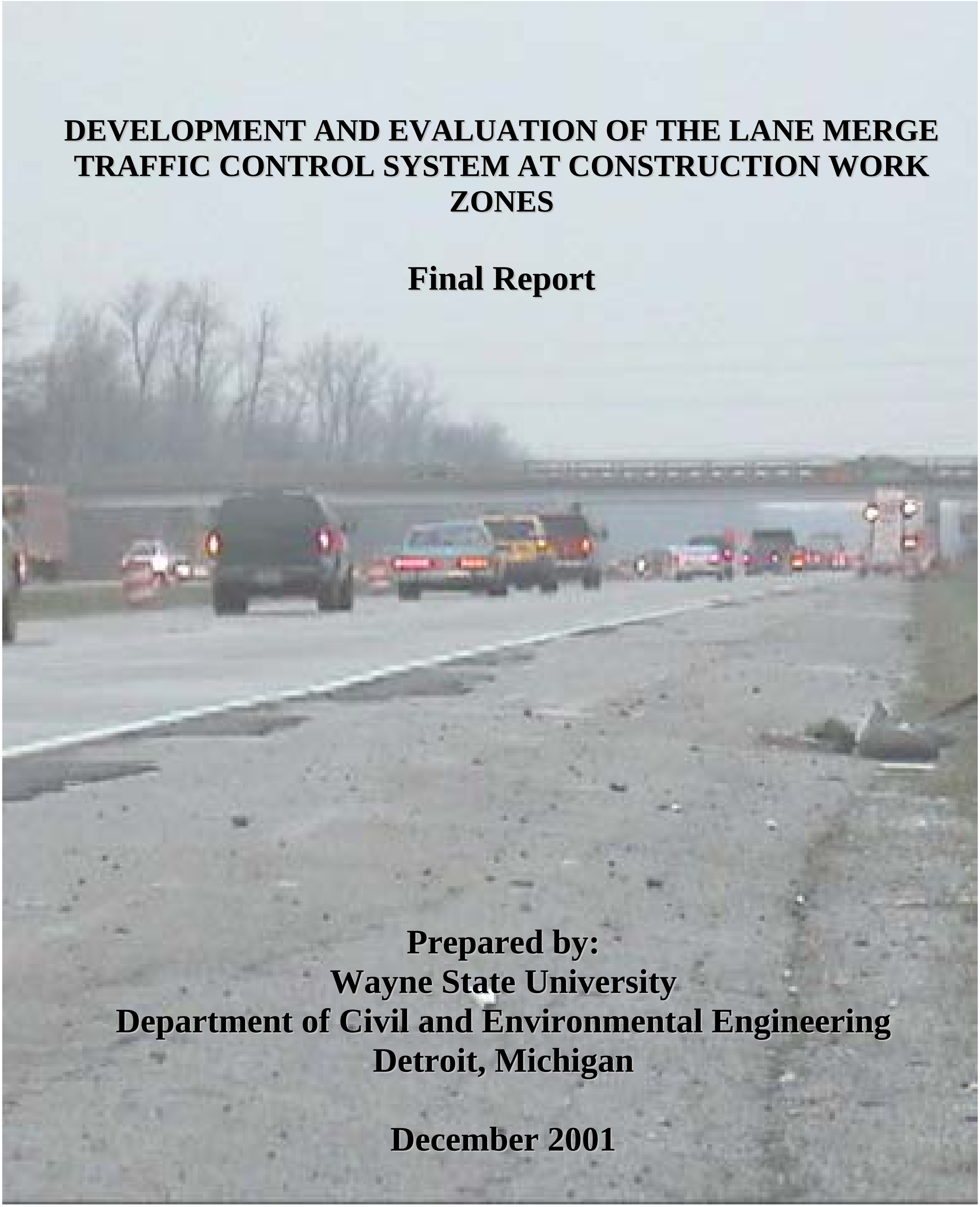

DEVELOPMENT AND EVALUATION OF THE LANE MERGE TRAFFIC CONTROL SYSTEM AT CONSTRUCTION WORK ZONES

Final Report

Prepared by:
Wayne State University
Department of Civil and Environmental Engineering
Detroit, Michigan

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16. Abstract
The majority of safety hazards and resulting traffic crashes that occur in lane closure areas in work zone are often due to the aggressive behavior of some drivers. The late lane merge phenomenon occurs when some drivers try to avoid slow moving traffic by traveling in the lane that is about to end, and then attempt to force merge in the through lane at the last moment. In an attempt to alleviate such aggressive driver behavior at work zones an innovative traffic control system was tested in Michigan. The Michigan Department of Transportation (MDOT) began a pilot project to study the effectiveness of a lane merge traffic control system (LMTCS), creating an enforceable no passing zone to encourage motorists to make an early merge. In Phase I of this study, test and control sites were examined in order to evaluate the effectiveness of the Michigan LMTCS, in terms of reducing delay, driver behavior and the effects of police enforcement. The research efforts for Phase II involved the development of an optimal traffic control system for work zone lane merges based on the experiences of the Phase I study and field testing of the same. During the Phase II, a comparison of the before and after data indicated that for similar flow rates, the average speeds increased. This may be due to the smoother traffic flow created by the dynamic LMTCS. Also, the average delay per vehicle to pass through the work zone and the number of aggressive driving maneuvers decreased due to the LMTCS.

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EXECUTIVE SUMMARY

The Michigan Department of Transportation (MDOT) began a pilot project to study the effectiveness of the dynamic lane merge traffic control system (LMTCS) in the construction season of the year 2000. Test sites for the LMTCS were solicited from various construction projects planned for the state freeway system, and the system was implemented at five locations throughout Michigan. The Wayne State University (WSU) research team became involved in the project to study the system's applicability and effectiveness to work zone safety and improvements in traffic flow after the implementation of the system at the initial test sites. The objectives of this study were to analyze and evaluate the LMTCS, in order to assess its effectiveness and to develop a lane merge traffic control system for Michigan's construction zones.

The dynamic LMTCS was tested during two consecutive construction seasons in Michigan. A static version of the LMTCS was also tested. In Phase I of this study, four test sites and four control sites were examined in order to evaluate the effectiveness of the Michigan LMTCS, in terms of reducing delay at the merge point, driver understanding and compliance of the system and the effects of police enforcement. The efforts for the Phase II (Spring, Summer and Fall 2001) study involved the development of an optimal traffic control system for work zone lane merges and field-testing to determine its effectiveness. The static LMTCS was not included in Phase II due to the unreliability of flashers being activated and deactivated before peak periods. In most instances the flashers were continually activated causing drivers losing confidence in the static LMTCS system.

System Description

The Michigan dynamic LMTCS consists of traditional work zone traffic control devices along with a system of dynamic "Do Not Pass/When Flashing" signs, to create a no passing zone to minimize late lane merges, to minimize aggressive driver behavior, and delay at the taper area.

In this system, signs are placed in advance of the taper section for the lane closure. A series of "Do Not Pass/When Flashing" signs are placed near the lane merge area.

These signs are mounted on trailers, along with sensors that can detect and monitor traffic volumes and occupancy. Once traffic slowdowns are detected, the next upstream "Do Not

Pass/When Flashing" signs are set to change into flashing mode in order to prompt drivers to change lanes even earlier, as compared to the low traffic volume condition. The sign including the trailer assembly for the dynamic LMTCS is shown on Figure ES-1.

Figure ES-1. Dynamic LMTCS Sign and Trailer Used in Michigan

The "Do Not Pass/When Flashing" sign closest to the taper is always activated and in the flashing mode. When the sensor on this sign detects traffic beginning to back up, it sends a signal to the next upstream sign, based on a preset level of occupancy rate in order to activate the sign to the flashing mode. Once activated, it will remain activated for the minimum preset lamp time (5 minutes) and then stop flashing, unless another signal is sent from the downstream sign. If back ups continue, the sensors transmit signals to the next upstream sign to keep it activated. This communication between the dynamic signs occurs for all of the dynamic signs except for the one closest to the taper, which is always in the flashing mode. When traffic in the upcoming closed lane encounters the "Do Not Pass/When Flashing" signs, they are not allowed to pass any vehicles in the adjacent through traffic lane, as per the regulation.

Summary of Findings

The summary of the data collected and the conclusions of the dynamic LMTCS tested in Michigan are as follows:

1. The dynamic LMTCS can be very helpful in reducing aggressive driver behavior, increasing safety and reducing delay at work zones where lane closures are necessary.

2. In order to utilize this system in the most efficient manner, focus must be placed on making sure that the driver understands and realizes the need for such a system. One approach to sending the appropriate message to drivers is to adjust the system based on expected traffic conditions (flow, speed, and density) in relation to the system settings and signing layout. The refinement of sensor settings, sign spacing and sign placement strategies developed as a part of this project, allowed for a more effective use of the dynamic LMTCS in Michigan.

3. The results of the Phase I study indicated that motorists may not have understood the sign message of "Do Not Pass/When Flashing", since many drivers were observed passing other vehicles through the series of flashing signs.

4. The data collection and analysis performed as a part of the Phase I efforts did not reveal any significant findings with respect to travel time and delay, which may possibly have been due to the non-optimal system settings and layout plan. However, the following observations were noted:
    - More aggressive driver behavior was observed at the static LMTCS than the dynamic LMTCS for similar flow rates.
    - Police enforcement had a positive impact on reducing the amount of aggressive driver behavior in the work zones.
    - Drivers may have been confused by the dynamic LMTCS due to the non-optimal system layout and often arbitrary sensor settings.

5. As a part of the Phase II study, several modifications were made to the system layout in order to address the issues discovered during the Phase I study. These modifications were based on the human factors and "Positive Guidance" analyses and included revising the signing sequence, spacing between dynamic signs and incorporating an additional illuminated sign in order to further instruct the drivers on how to respond to the system. The following are the modifications that were made to the dynamic LMTCS:
    - The sequence of signs placed after the dynamic sign trailers were changed to incorporate static "Do Not Pass" signs placed in between the standard lane closure warning and dynamic "Do Not Pass/When Flashing" signs.
    - The spacing of the dynamic signs was increased from 700 feet to 1,500 feet.
    - A changeable message sign was placed upstream of dynamic signing with "Merge Right" or "Merge Left" text with an arrow symbol to provide motorists with additional cues on how to respond to the system and where to merge to the open through lane.
    - In order to implement right lane closures, as opposed to only left lane closures, sign panels with text "Right Lane/Left Lane" were mounted above the "Do Not Pass/When Flashing" signs to inform motorists of the left lane or right lane closures respectively.

6. During Phase II, data collection and analysis of the sensor settings were performed in order to determine optimal values. The parameters studied included threshold percent occupancy and sensor detection time. Values for these parameters were calculated and tested in the field. Analyses were then performed to determine optimal sensor settings. These values were then tested and refined as a part of the Phase II data collection.
7. A 'before and after' study was performed for the M-53 construction project in Macomb County. The 'before' data was collected at the site with a lane drop in place using traditional lane closure signage. The 'after' data was collected at the same site with the dynamic LMTCS in place. The data collection and analysis performed at the M-53 sites revealed that the dynamic LMTCS was effective in improving the traffic operations and reducing safety risks through the work zone. The following are some specific findings:
    - At similar flow rates during the 'before' and 'after' period, the average travel

speed based on the peak period travel time runs increased slightly after the implementation of the dynamic LMTCS at both the NB and SB M-53 sites.

- The average peak period travel time delay decreased with the dynamic LMTCS at both M-53 sites.
- The average peak hour flow remained similar for construction zones with and without the dynamic LMTCS at both the M-53 sites.
- Based on the peak hour travel time runs, the average number of stops in the construction zone for the NB and SB sites decreased with the implementation of the dynamic LMTCS. The average duration of the stopped time delay per run, also decreased for both the sites when equipped with the dynamic LMTCS.
- The number of aggressive driver maneuvers during the peak hours reduced dramatically at both the NB and SB M-53 sites.

9. The results of a statistical analyses of the mean travel time delay data, indicated that the mean delay "before" was significantly higher than the mean delay "after" the implementation of the dynamic LMTCS.

10. The results of the economic analysis performed as a part of this study (based on one test site) indicated that the dynamic LMTCS will be economically beneficial and achieve B/C ratios greater than one, if a value of time of $3.80 per person hour is assumed for travel time savings.

Recommendations

The recommendations for future implementation of the dynamic LMTCS in Michigan are as follows:

1. The dynamic LMTCS can be implemented on highways with two lanes in each direction reduced to one lane during construction. The dynamic LMTCS may also be considered for three lane highways reduced to two lanes at freeway work zones. However, additional signing may be necessary to inform/instruct motorists how to respond to the system. It is important to note that a pilot study may be necessary to determine the effectiveness of the

work zone scenario of three lanes reduced to two lanes. Such pilot study should determine the criteria for LMTCS applications.

2. The dynamic LMTCS may be implemented at work zones with or without an interchange, including entrance and exit ramps in the immediate vicinity of the work zone. If interchanges are located within the work zone, care should be taken to ensure that the sensor settings are properly designed to respond to fluctuations in traffic. Guidelines for the sensor settings are included in Appendix III for seven different scenarios for entrance and exit ramp locations. However, these settings should be monitored in the field to verify that the system is operating efficiently.

3. The dynamic LMTCS can be used at stationary construction projects, such as bridge repair/rehabilitation, such as repaving or repair of long highway segments. If the construction activity includes relocation of the system, then pay items should be included in the construction contract for the re-location and the implementation of the lane merge traffic control system. Relocations of the system should be kept to a minimum, possibly one to two per project. If the relocations of the dynamic LMTCS are included project, the construction specification should include the availability of a work site traffic supervisor (WTS) knowledgeable about the dynamic LMTCS. The system is **not** designed to be set up and taken down on a daily or weekly basis. It is important to note that the set up and calibration of the system takes 3-5 hours for each system move.

4. The construction zone must be in place during the peak hours of travel. The dynamic LMTCS is recommended for highway projects that experience moderate to high traffic volumes prior to construction. Guidelines for implementing the dynamic LMTCS based on AADT and peak hour volumes were developed based on an analyses of expected delay using the Highway Capacity Software, as well as the traffic flow and system performance observed at the test sites. The guidelines (two lanes to one lane) are as follows:

    - Directional AADT: **21,500 to 34,500 vehicles per day** per direction

- Average weekday AM and/or PM peak period volumes prior to construction (2 peak hours per day): **2,000 to 3,000 vehicles per hour** per direction

Estimated guidelines for using the LMTCS for a lane closure of three lanes reduced to two lanes are as follows:

- Directional AADT: **34,500 to 48,500 vehicles per day** per direction
- Average weekday AM and/or PM peak period volumes prior to construction (2 peak hours per day): **3,000 to 4,500 vehicles per hour** per direction

The criteria for three lanes to two lanes work zone should be tested and refined by further field study.

Please note that during construction, the traffic volumes may slightly reduce since some drivers may choose to travel on alternate routes to avoid the work zone. Thus, the traffic volume guidelines presented are for the pre-construction traffic volumes observed on a typical day.

5. The implementation of the dynamic LMTCS will be effective for projects with short and long term durations. As per conversations with equipment suppliers, if the system is implemented at short term projects (less than three week duration), the cost of implementing and operating the system will be reduced. If the system is implemented for long term projects, the system may have to be relocated and will be associated with higher implementation and continuous maintenance costs.

6. The dynamic LMTCS may be implemented when closing either the left lane or right lane in a work zone. For a right lane closure, an additional "Right Lane" or "Left Lane" sign panel (depending on which lane is closing) should be added to the dynamic sign trailer.

7. The layout for the dynamic LMTCS, as recommended in this report, should be used for all future system implementation. This layout includes five dynamic sign trailers and a changeable message sign with text "Merge Right" (or Left) with an arrow symbol.

8. A media campaign should be accompanied with the implementation of the dynamic LMTCS in order to educate the motoring public to the benefits of the system, the changes in the law which prohibits passing in work zones with lane closures, the risk of aggressive driving in work zones and the dangers of provoking road rage.

9. When implementing the dynamic LMTCS in areas where drivers may not be familiar with the system, police enforcement should be included in order to inform/warn drivers that are unintentionally violating the no passing zone, as well as, ticketing those drivers that are blatantly disobeying the law. It is expected that once the system gains considerable familiarity, such aggressive enforcement and educational efforts by the police may not be necessary.

INTRODUCTION

Safety at construction/work zones is a paramount concern to transportation officials and the motoring public. Safety hazards encountered in highway work zones are numerous. They encompass an area of the highway that mixes drivers, workers and unfamiliar objects in a normally familiar setting. The majority of safety hazards and resulting traffic crashes in work zones occur in lane closure areas, often due to the aggressive behavior of some drivers. For example, in Michigan, approximately 6,950 work zone crashes occurred in 1999, of which, 47% occurred in lane closure areas. (*1*) One situation that contributes to hazards commonly found in lane closure areas pertains to the 'late lane merge phenomenon'.

The 'late lane merge phenomenon' occurs when some drivers try to avoid slow moving traffic by traveling in a lane that is about to end, and then attempt to force a merge at the last moment. This is an extremely dangerous driving maneuver for the driver, other motorists, and also, workers in the construction zone. This type of late lane merge may cause hostility and "road rage" among the other patiently waiting drivers. It also increases delay to motorists by creating a sudden interruption of traffic flow, and increases the risk of safety hazards to those drivers on the roadway who are following traffic regulations.

Several studies have been performed in the United States to investigate and mitigate this driver behavior problem. Specifically, past published literature has identified two systems used in lane closure areas in work zones that have already been tested in the US. These systems were initiated by the Indiana Department of Transportation (IDOT) and the Pennsylvania Department of Transportation (Penn DOT). These two systems are very different, in that they operate under completely opposite assumptions.

The lane merge traffic control system tested by IDOT (*2,3*) uses a series of "Do Not Pass/When Flashing" signs placed in advance of the taper area creating an enforceable no passing zone, to encourage motorists to make an early merge. This traffic control system was designed to create a smooth and uniform flow of traffic as the vehicle proceeds through the lane closure area. (*2,3*)

The Penn DOT system however, is based on directing the motorists to merge late at lane closures in order to increase the capacity in the work zones. This traffic control system is opposite of the traffic control systems used by IDOT in that it encourages drivers to merge late, near the taper, using a "Merge Here Take Your Turn" sign. (*4*)

In the past few years, state officials in Michigan have become increasingly concerned with safety hazards and road rage issues in work zones, and particularly, at lane closures. In order to address these issues, the Michigan Manual of Uniform Traffic Control Devices was revised to allow no passing zones to be implemented in work zones through the use of "Do Not Pass" signs. This allowed the enforcement of aggressive driver actions at work zone related lane closures in Michigan.

Beginning in the summer of 2000, the dynamic lane merge traffic control system (LMTCS) was implemented at several locations throughout the state of Michigan. The dynamic LMTCS implemented in Michigan has similar features to that of the system used in Indiana. Since this system is new in the state of Michigan, a project was initiated to study and evaluate the system's performance. Wayne State University (WSU) researchers were involved in this project to study the initial pilot test sites in Michigan, and to develop a system which will alleviate the aggressive passing maneuvers, and consequently, create a safer driving environment for all travelers.

BACKGROUND

As a part of this project, a literature review was performed for lane merge traffic control systems in order to assess the effectiveness of the systems tested in other states. The following is a summary of the research efforts conducted on LMTCS in the past.

Indiana Department of Transportation Early Merge System

In Indiana, studies were conducted to address the late merge phenomenon in construction/work zones. (*2,3*) The problem with late merges arise when aggressive drivers pass a line of slow moving vehicles that are backed up due to a lane closure, and force their way in the traffic stream, which causes frustration and further delay to the other motorists. Late merges also create turbulence in the traffic stream, and result in increased crash risk and delays. The IDOT system attempted to mitigate this problem by installing a series of dynamic "Do Not Pass/When Flashing" signs in advance of the taper. These signs are equipped with sensors that monitor traffic density and congestion. When the density is high, and congestion and traffic backups are detected, a signal is transmitted to the next upstream dynamic no passing sign, to activate the sign's flashing signal. (*2,3*)

In the IDOT's lane merge traffic control system, the primary warrant for the dynamic system's use is the anticipated or observed presence of congestion at the entry point of the work zone. The system's use is recommended if the congested segment is longer than approximately two (2) miles. If the maximum length of the congested area is less than one (1) mile, it does not warrant the system's use as per the criteria established by IDOT. The maximum congested segment can be determined through direct observation, or can be calculated using the capacity of a work zone based on the type of construction activity and traffic volume. (*2,3*) According to Indiana's guidelines, once the system is warranted in a construction zone, the layout and system parameters must be determined.

In this system, the minimum sign spacing between any two dynamic signs is 150 m (≈ 500') and is based on the time and distance necessary, for a driver to respond to any one of the signs. The signing system recommended by the Indiana DOT uses **three static** "Do Not Pass" signs with a range of **two to six dynamic signs**, based on the length of congestion, as shown in Figure 1.

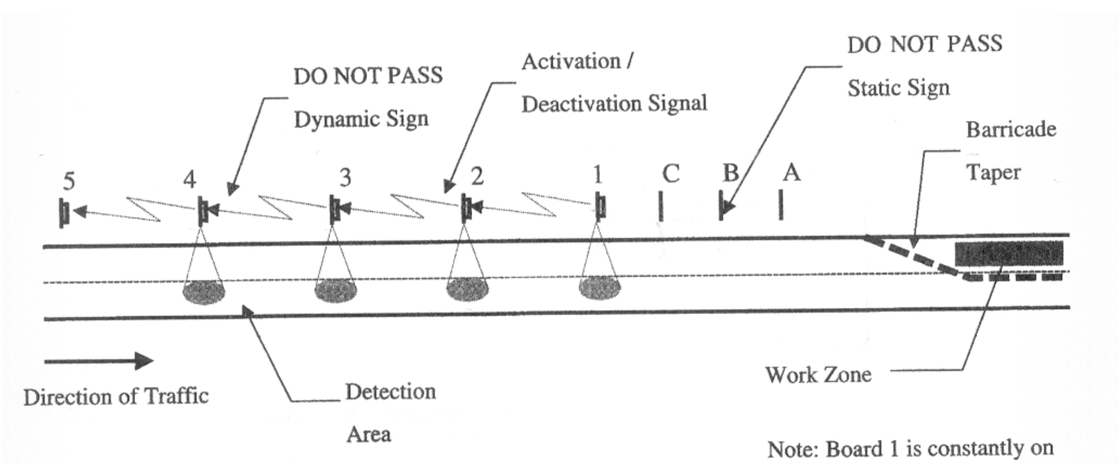


Figure 1. Lane Merge Traffic Control System used by IDOT
[Source: Manual of the Indiana Lane Merge Control System- Final Report *(2)*]

The system parameters include sensor detection time, threshold occupancy, and lamp time. The sensor detection time is the period of time that the sensor is monitoring the presence of traffic in the detection zone. Occupancy levels are defined as the percentage of the total monitoring period (sensor detection time) that vehicles are present in the detection zone. When the measured occupancy levels exceed the preset occupancy threshold, a message is sent to the next upstream sign and it begins to flash. The lamp time is the time that the sign remains activated, once a signal is received.

Research in Indiana has indicated that the recommended optimum threshold occupancy for the activation of the dynamic sign was 30 percent for a typical detection zone of 6 feet. This means that the dynamic sign sensors will become activated when vehicles are detected in the detection zone for at least 30 percent of the sensor detection time. This value was included in the Indiana report (*2*). The authors of the report mentioned that this occupancy level was developed based on the results of a simulation model representing a work zone with dynamic no passing zone signs. The IDOT manual states that "research has indicated that the system's performance does not change significantly with the change of the threshold occupancy, if the threshold occupancy stays in the range between 25 and 35 percent". (*2*) In addition, the sensor detection time was determined to be five minutes in order to avoid any premature or "sluggish" sign activation. Once a sign is activated, the sign will remain activated for a lamp time of at least five minutes, in order to prevent the premature activation of signs. (*2*)

Tarko, Shamo, and Wasson (*3*) performed a study to investigate driver compliance with the signs, travel times, and passing maneuvers through the merge area of construction zones where the dynamic LMTCS will be used. This research was based on a series of simulation studies, since a fully deployed system was not in place, and limited field observations of the system operated manually. Preliminary research on this system has shown safer driver behavior, and decreased travel time through these transition areas. However, the authors state that the long-term capacity and safety effects of this system have not yet been quantified. (*3*)

One advantage of the IDOT system which creates an enforceable no passing zone in construction areas, is that aggressive driver behavior can be altered through the work zone by citing the violators for improper driving actions. Alleviating aggressive driver behavior at work zones will provide a safer environment for motorists and construction workers.

Pennsylvania Department of Transportation Late Merge System

The Penn DOT developed the "late merge" concept for work zone lane closures in order to reduce the length of queues and reduce road rage that often develops among drivers due to construction related stops and delays. This traffic control system is completely opposite from the traffic control systems used by IDOT in that it encourages drivers to merge late, near the taper. The Penn DOT Late Merge system use is intended for highways where the traffic demand exceeds the capacity of the work zone. (*4*)

Pesti, Jessen, Byrd, and McCoy (*4*) assessed this "late merge" traffic control system and compared it with traditional lane closure methods. Traditional lane closure traffic control systems typically include advance lane closure warning signs and lane-reduction symbol signs placed on both sides of the roadway, in advance of the taper with a flashing arrow panel placed at the beginning of the taper.

In order to address issues associated with congestion in advance of the lane closure, the "late merge" concept was developed by PennDOT which uses the sign "Use Both Lanes to Merge Point" placed in advance of the lane closure on both sides of the roadway. These signs are followed by "Road Work Ahead" and advance lane-closed signs. Finally, "Merge Here Take Your Turn" signs were placed on both sides of the roadway near the beginning of the taper, as shown in Figure 2.

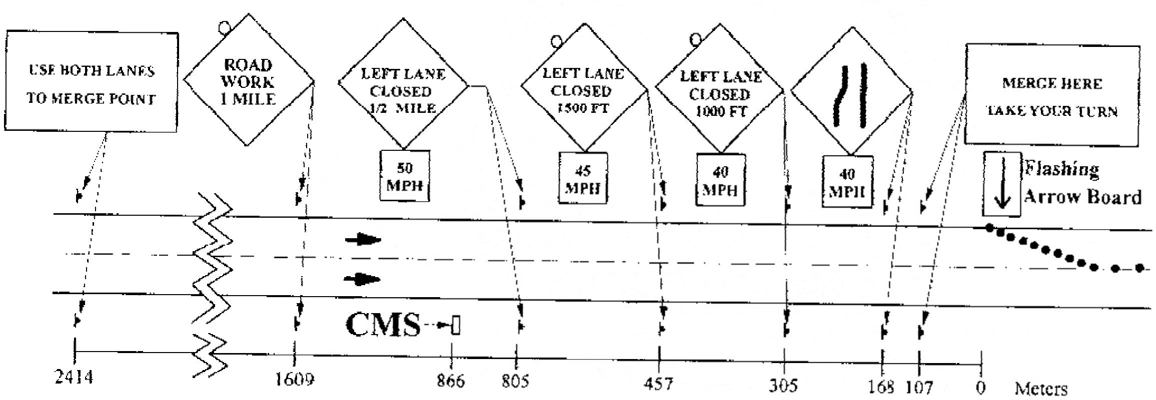


Figure 2. Late Merge Traffic Control System Used by PennDOT
[Source: Pesti, Jessen, Byrd and McCoy *(4)*]

The authors conducted a field study of the “late merge” system of construction zone traffic control to evaluate the operational effects and to assess driver’s opinions of its applicability (*4*). In this study, data involving traffic volumes, speed, density, lane distribution, as well as, driver behavior and traffic conflict characteristics were collected.

The results of the lane distribution data indicated that both passenger cars and trucks move as soon as possible to the continuous lane after passing the “Use Both Lanes to Merge Point” sign, instead of remaining in the discontinuous lane until they reach the merge point. The results of the speed study indicated that the mean speeds in the left discontinuous lane were higher than in the right continuous lane, and vehicles slow down as they got closer to the lane closure. The mean travel speeds for both passenger vehicles and trucks exceeded the advisory speed limit, and the posted speed limit, through the construction zone. The results of the density study were used to measure the capacity through the work zone. It indicated that in terms of passenger cars per hour, the work zone capacity of the “late merge” is about 18 percent higher than traditional lane closure measures (*4*).

Traffic conflict data were also collected as a part of the study, in order to assess the effects of the late merge traffic control system in the work zone. The authors observed three types of conflicts including forced merges, lane straddles and lane blocking. The results of the traffic conflict study indicated that forced merges were the most predominant ones. In addition, through linear regression analysis, a direct relationship was established between traffic conflicts and density, especially with the forced merge type of traffic conflict. The authors also noted that less traffic conflicts were observed with the late merge traffic control system, in comparison to traditional methods of work zone traffic control. (*4*)

The authors concluded that “the concept might not be working as effectively as it is capable of”. Based on the lane distribution data obtained during both free-flow and congested-flow periods, it can be concluded that some drivers did not follow the directions given by the control signs, thus reducing the effectiveness of the merging operations. Most of them tried to move into the open lane well before the merge point.” (*4*)

They also concluded that the late merge system is more effective than traditional traffic control systems in terms of safety and efficiency of merging operation in advance of lane closures on interstate highways. (*4*)

Author of the study (*4*) concluded that the "late merge" traffic control system is not as effective as was originally anticipated; since drivers are not responding to the traffic control system through the lane closure area. The "late merge" system is based on what many researchers are trying to prevent. This system may even violate some driver's expectation by forcing drivers to merge late, and thus, it may not operate as planned.

Comparison of the Lane Merge Systems

In another paper published recently by McCoy and Pesti *(5),* the authors compare the 'late merge' system developed by PennDOT and the 'early merge' system developed by IDOT with the traditional lane merge system used by the Nebraska Department of Roads (NDOR), referred to as the 'NDOR merge system'.

In the NDOR merge system, advanced lane closure signs are placed on both sides of the road at one (1) mile and half (½) mile distances upstream of the lane taper area. In addition, lane reduction symbol signs (on both sides of the road) are placed 1,500 feet upstream of the taper with a flashing arrow panel placed at the beginning of the taper *(5)*.

In this paper, the authors examine the advantages and disadvantages of the 'late merge' and 'early merge' concepts in terms of their operational and safety characteristics under congested and uncongested traffic flow conditions. Also, a new concept, the *dynamic late merge* is described which incorporates the late merge system with the NDOR merge system "on the basis of real-time measurement of traffic conditions in advance of the lane closure" *(5)*.

The NDOR conducted field studies to compare the Indiana lane merge system with the NDOR system. The results of the comparison between the systems showed that in the early merge system, the vehicles moved up into the open lane much sooner and the merging occurred more uniformly over a much longer distance. This made the merging smoother and reduced the number of forced merging operations, but the vehicle travel time was higher *(5)*.

The NDOR also conducted field studies to compare the safety and operational effects of the PennDOT late merge system and the NDOR merge system. The results of these studies indicated that the conflict rates are lower with the late merge system and the capacity of the late merge system is higher than the NDOR merge system, by approximately 20 percent. With the late merge system, there is potential for drivers to be confused at the merge point, especially during uncongested conditions where the travel speed is high, and the volume is low. This driver confusion may adversely affect safety *(5)*. The authors stated that the late merge system " may not be the best system during off-peak periods" *(5)*.

The concept of a "dynamic late merge system" was developed and is intended to mitigate driver confusion at the taper area. This system would switch from the 'late merge' system to the conventional NDOR merging system on the basis of real-time measurements of traffic flow. The 'late merge' system would be effective during the peak periods, while during the off-peak periods, the conventional system would be effective.

The 'dynamic late merge system' would consist of a series of advanced signs that would be activated, to advise the drivers to "Use Both Lanes to the Merge Point" when congestion is detected in the open lane. The detection and communication system would be similar to that used in the Indiana dynamic lane merge system. A sign would then be placed at the merge area, advising drivers to "Merge and Take Your Turn". When congestion clears, the signs would be deactivated to inform drivers to travel through the area as a traditional merge system.

The authors note some important issues associated with the new 'dynamic *late* merge system' in terms of the lane distribution and speed between the open and closed lanes, while switching from the NDOR merge system and the late merge system. When the system switches to the late merge system, the traffic crash potential may be high if drivers in the slower open lane, attempt to merge into the higher speed closed lane before the flow in the lanes becomes equal. The authors suggest that in order to minimize crash potential during the transition, speed control measures be used, as well as providing additional messages to inform motorists how they should traverse through the system. They also recommend that future research is necessary to determine the driver information system necessary for the ‘dynamic late merge system’ concept, and the protocols and safety measures necessary at the transition period *(5)*.

STUDY OBJECTIVES

The Michigan Department of Transportation (MDOT) began a pilot project to study the effectiveness of the dynamic LMTCS in the construction season of the year 2000. Test sites for the LMTCS were solicited from various construction projects planned for the state freeway system, and the system was implemented at five locations throughout Michigan. The WSU research team became involved in the project to study the system’s applicability and effectiveness to work zone safety and improvements in traffic flow, after the implementation of the system at four initial test sites. The objectives of this study were to analyze and evaluate the LMTCS, in order to:

- Assess driver understanding of the signs through their driving actions,
- Quantify aggressive driving maneuvers, with and without police enforcement,
- Assess the effectiveness of the dynamic LMTCS in terms of traffic operations and safety,
- Develop a system which will improve traffic safety and operations through construction zone lane closures

The dynamic LMTCS was tested during two consecutive construction seasons in Michigan. In Phase I of this study, four test sites and four control sites were examined in order to evaluate the effectiveness of the Michigan LMTCS, in terms of reducing delay at the merge point, driver understanding and compliance of the system, and the effects of police enforcement. The Phase I efforts were conducted during the late summer and fall of 2000. MDOT selected the sites for the dynamic LMTCS, developed the system layout and implemented the system prior to WSU’s involvement in the study. The research efforts for Phase II (Spring, Summer and Fall 2001) involved the development of an optimal traffic control system for work zone lane merges and field-testing to determine its effectiveness.

SYSTEM DESCRIPTION

The Michigan LMTCS consists of traditional work zone traffic control devices, along with a system of static and/or dynamic “Do Not Pass” signs to create a no passing zone and minimize late lane merges, aggressive driver behavior and delay at the taper area.

In both the dynamic and static systems, signs are placed in advance of the taper section for the lane closure. A series of “Do Not Pass/When Flashing” signs are placed near the lane merge area.

In the dynamic system, the signs are mounted on trailers along with sensors that can detect and monitor traffic volumes and occupancy. Once traffic slowdowns are detected, the next upstream “Do Not Pass/When Flashing” signs are set to change into flashing mode in order to prompt drivers to change lanes even earlier, as compared to the low traffic volume condition. The sign including the trailer assembly for the dynamic LMTCS is shown on Figure 3.

Figure 3. Dynamic LMTCS Sign and Trailer Used in Michigan

In the dynamic system, the “Do Not Pass/When Flashing” sign closest to the taper is always activated and in the flashing mode. When the sensor on this sign detects traffic beginning to back up, it sends a signal to the next upstream sign, based on a preset level of occupancy rate in order to activate the sign to the flashing mode. Once activated, it will remain activated for the minimum preset lamp time (5 minutes) and then stop flashing, unless another signal is sent from the downstream sign. If back ups continue, the sensors transmit signals to the next upstream sign to keep it activated. This communication between the dynamic signs occurs for all of the dynamic signs, except for the one closest to the taper which is always in the flashing mode. When traffic in the upcoming closed lane encounters the “Do Not Pass/When Flashing” signs, drivers are not allowed to pass any vehicles in the adjacent through traffic lane as per the regulation.

In the static system, flashing beacons are mounted on the “Do Not Pass” signs. In order to activate these signs, the beacons are manually turned on or off depending on anticipated times of congestion.

PHASE I STUDY OF THE MICHIGAN LMTCS

Site Description

The dynamic LMTCS was implemented and tested at four work zones as a part of the Phase I study during the year 2000 construction season at the following locations:

- Northbound (NB) I-75 in Bay County
- NB I-69 in Eaton County
- Southbound (SB) I-69 in Branch County
- NB US-31 in Muskegon County

In addition, the static LMTCS was implemented at the following three work zones:

- SB I-69 in Eaton County
- SB US-31 in Muskegon County
- US-27 in Roscommon County

Only two of these locations were included in the Phase I evaluation (SB US-31 and NB I-69) study.

The system installation was solicited from local MDOT construction offices and minimal criteria were used when selecting the sites for Phase I testing. The only requirements, as stipulated by MDOT, included using the system for one-lane closures (left lane) for a two-lane (same direction) freeway segment. Thus, if the construction activities took place in the right lane, initially, a left lane closure was established and then traffic was shifted for a right lane closure. This was done because MDOT thought that no passing zones should only be permitted in the left lane, since motorists typically use the left lane for passing maneuvers.

The LMTCSs were deployed at the same time the work zones were set up, thus it was necessary to select control sites in order to perform an evaluation using the comparative parallel study. The control sites were selected for the same highways as the dynamic LMTCS test sites, but for the opposite direction of travel.

All four of the dynamic LMTCS test sites consisted of a two-lane (each direction) freeway section with a left lane closure. The LMTCS included five dynamic “Do Not Pass/When Flashing” signs mounted on trailers equipped with sensors. The overall system also included various traditional work zone warning signs.

The two static control sites consisted of two-lane freeway sections with a left-lane closure. The system layout for the LMTCS was similar to the dynamic system; however, the signs were not mounted on trailers and sensors were not used. Instead, the five static signs were equipped with beacons that were always flashing and manually turned on or off.

The remaining two control sites consisted of two-lane freeway sections with traditional work zone traffic control signing.

The following table shows the Annual Average Daily Traffic (AADT) for the Phase I Sites:

LOCATION	AADT* (VEHICLES PER DAY) FOR TOTAL OF BOTH DIRECTIONS OF TRAVEL
Bay and Arenac Counties I-75	24,000
Branch County I-69	18,700
Eaton County I-69	18,100
Muskegon County US-31	41,900

Data Collection

Travel time and delay studies were performed at the test sites, as well as at all the control sites, during various times of the day. These studies were conducted using the floating car method where a two-person team was used with one person driving through the zone and the second person recording the travel time at specific locations. The study team traveled through each test and control site for at least 15 runs.

Travel time data was recorded for a specified distance through the advanced warning area, from the first warning sign the driver encounters, until just after the taper. In addition, the location and duration of any stopped time delay through the advanced warning area were also recorded. At the dynamic and static sites, the status of the signs (flashing or not flashing) were recorded. Aggressive driver behavior data and vehicle merge locations were also observed and recorded during the travel time runs. These observations provided information on driver behavior characteristics through the entire merge area for vehicles in close proximity to the test car driver. The test car driver also observed the presence, or absence of police enforcement through each run.

The total travel time through the advanced warning area was summarized, and estimated delay values were calculated. Travel time delay is defined as the difference between the driver's desired total time to traverse a section of roadway and the actual time required to traverse it. *(6)* The total delay per run was determined by calculating the estimated travel time for an assumed travel speed, minus the actual travel time per run.

Traffic volume data was collected concurrently with the travel time runs using a video camera or by manual observation with tally boards at the test and control sites, in order to determine the specific traffic flow associated with each run. A video study was performed to collect information on driver behavior through the LMTCS. Traffic volume, average travel speed and delay data are summarized in Table 1 for the Phase I study.

Table 1. Operational Characteristics for Phase I

	Test sites (Average of 4 sites)	**Control Sites (Average of 4 sites)**
Average Travel Speed Based on Travel Time Runs	63 mph	58 mph
Average Delay	23 sec/veh	61sec/veh
Average Flow	857 vph	839 vph

The details of the traffic operations data collected as a part of Phase I, is included in Appendix I.

During data collection, it was observed that the number of signs activated, in relation to the traffic flow and speed, varied between the four sites where the dynamic LMTCS were installed. At one of the sites, low traffic flow conditions were observed during data collection, yet all five of the dynamic signs were activated, when only one (1) or two (2) signs should have been activated. At another site, during congested periods, only three signs were activated when all five should have been in the flashing mode.

Discussions with the contractor revealed that the system's parameters for sensor settings were set somewhat arbitrary. The system's performance could have been influenced by the improper setting of the system parameters.

The Phase I data did not reveal any significant findings with respect to travel time and delay, which may possibly have been due to the non-optimal system settings. However, the following observations were noted:

- More aggressive driver behavior was observed at the static LMTCS than the dynamic LMTCS for similar flow rates.

- Police enforcement had a positive impact on reducing the amount of aggressive driver behavior in the work zones.
- Drivers may have been confused by the dynamic LMTCS due to non-optimal system layout and often arbitrary sensor settings.

After the completion of Phase I, it was determined that Phase II of this study would include an investigation and identification of the optimal system layout and settings, as well as an evaluation of the system performance. The static LMTCS was not included in Phase II due to the unreliability of flashers being activated and deactivated before peak periods. In most instances the flashers were continually activated causing drivers losing confidence in the static LMTCS system. Expected driver behavior characteristics at work zones were studied by applying the 'Positive Guidance' concept in order to refine the dynamic LMTCS layout for Phase II of the study. The following is a summary of this research.

DRIVER BEHAVIOR AND ANALYSIS

Driver behavior through work zones depends on many factors, including the recognition of the intended merge warning signs, decision-making, vehicle control, risk taking and others. The 'Positive Guidance' *(7)* concept divides a hazardous roadway segment into a series of information handling zones based on the informational requirements and the temporal response requirements of the motorist at each point. The three issues with driver behavior are then summarized into the drivers <u>seeing</u>, <u>comprehending</u> and then, <u>making a decision</u> at these locations.

One other important driver behavior concept deals with 'driver expectancy'. This concept recognizes the fact that the driver not only responds to positive guidance devices present at a work zone, but also uses past experience in recognizing unusual driving environments. The concept of 'driver expectancy' must be considered while designing any traffic control system <u>because driver performance tends to be rapid, accurate and largely error free, when expectations are met</u>. Performance may be slow, inaccurate, or inappropriate when expectations are violated.

<u>Primacy</u> of information is another issue pertaining to driver behavior. Drivers get information from various roadway and roadway environmental features, traffic sign systems and other visual information provided along the roadway. The driver is always prioritizing various <u>information and cues</u> that he/she receives while driving. The driver is continuously prioritizing this

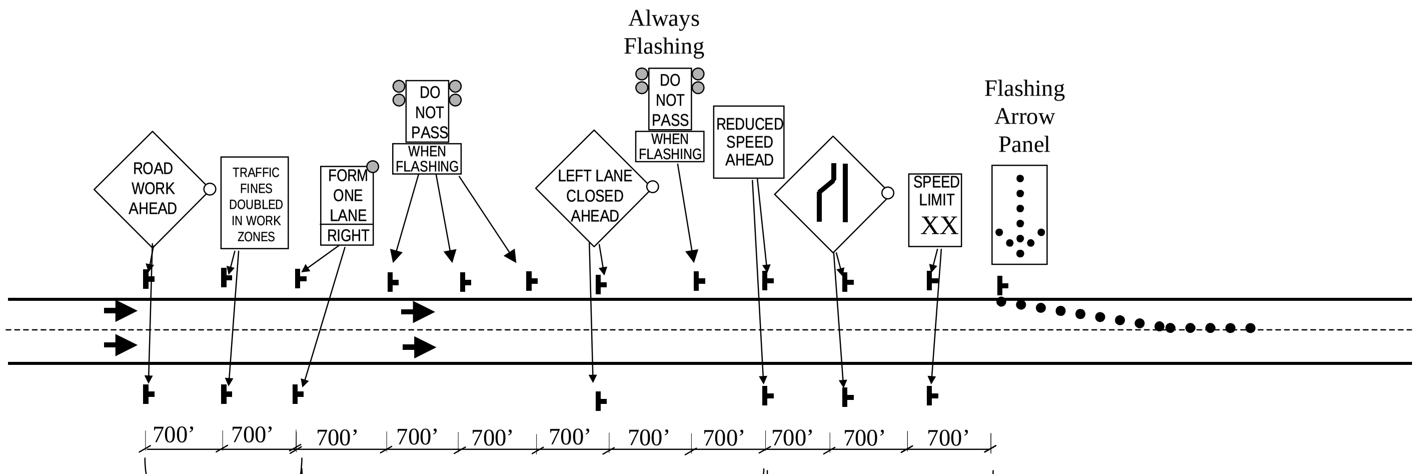
information and discarding the information that seems irrelevant or unimportant. The time gap between information is critical to a driver in order for him/her to retain the relevant information, and take appropriate action when the circumstances demand.

It has been observed from the driver behavior study in Michigan (Phase I), that some motorists were confused about the proper action to take while driving through the lane merge traffic control system. Several factors may have led to driver confusion, including non-optimal system layout, insufficient spacing between dynamic signs, the sign message of "Do Not Pass/When Flashing" being new and unfamiliar in this setting, and the installation of the system when not warranted that lead to non-compliance.

System Layout

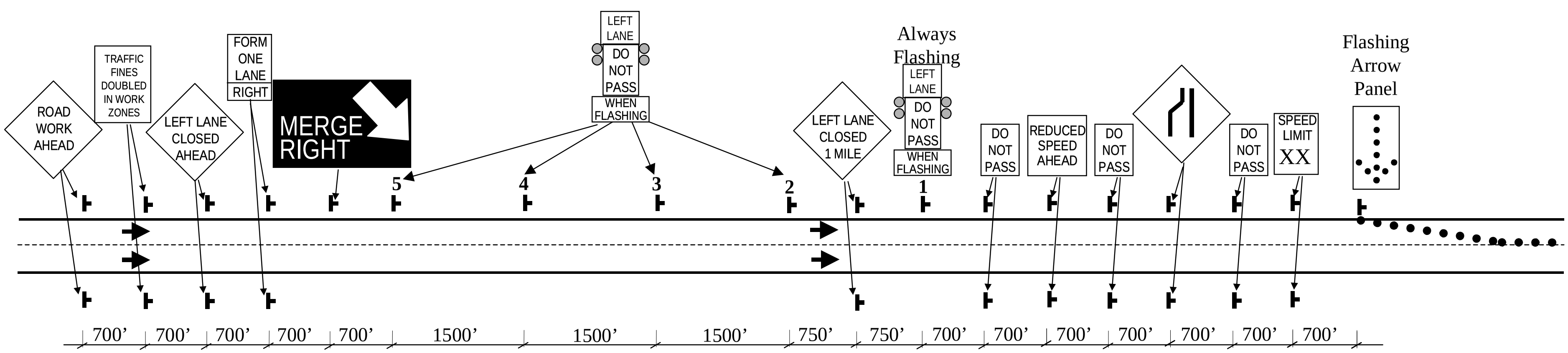
The system layout used in Michigan in Phase I (Figure 4a), included a series of advanced work zone signs, followed by a series of dynamic signs that create a no passing zone, followed by a series of work zone advisory signs just before the taper. The problem with this layout is mainly due to the signs between the dynamic LMTCS sign no. 1 and the taper. The no passing zone is intended to begin at the first flashing "Do Not Pass" sign and is continued through the taper area. In the Michigan system for Phase I, drivers did not understand that the no passing zone was still in effect, after the series of dynamic signs and unintentionally violated the no passing zone in this area since the zone was no longer signed to instruct the drivers not to pass the vehicles in the continuous lane.

As drivers entered the approach of a work zone, they were given information. This information was displayed on signs such as "Road Work Ahead", "Traffic Fines Doubled in Work Zones" and others. The next set of signs created a dynamic no passing zone. Comments from some police officers indicated that, some drivers were not familiar with this signing system, since it is new, and were confused on how to respond. Then, the next series of signs, including "Reduced Speed Ahead" and the lane reduction/transition sign, lead the motorists through the taper area and into the work zone. These signs created an environment that was once again, familiar to drivers in a normal work zone. The "Do Not Pass" signs were no longer present in this series of signs, yet the no passing zone was intended to be effective through the taper area. As a result, some drivers went back into the discontinuous lane, even if they originally obeyed the no passing zone. The purpose of the dynamic LMTCS is to encourage drivers to enter the lane drop area in one lane in order to avoid traffic conflicts and driver frustration at this critical area, yet no signs were provided.



• Phase I for a Left Lane Closure

(Source: “Lane Merge in Construction Zones, MDOT Office Memorandum, December 16, 1999)



(b) Phase II for a Left Lane Closure

LEGEND

○ Type A Warning Flasher (Required at Night)

Type B High Intensity Light

Traffic Flow

Figure 4. Schematics of the System Layout for a Left Lane Closure (a) Phase I and (b) Phase II

Spacing of Dynamic Signs

The sign spacing used in Phase I in Michigan was based solely on an operating speed of 65 to 70 mph, based on location, which resulted in a sign spacing of approximately 700 feet (Figure 4a, page 17). This spacing is too close to allow drivers the opportunity to respond properly to the sign, and thus, may decrease the efficiency of the system.

The spacing of the dynamic signs should be a function of driver perception/reaction time and operating speed. According to the human factors perspective, it takes a driver a certain amount of time to see, understand, and react to a traffic sign. Additional signs are placed downstream in case drivers did not react to the first sign, either because they forgot, or they did not have an opportunity to react. For example, assume, that it takes 5 seconds for a driver to see and understand a sign, and also assume that the message remains in a driver's memory for 10 seconds. Please note that a higher perception reaction time is being used in this example (typically 2.5 seconds is used) for two reasons. First, drivers are not familiar with the "Do Not Pass" sign in a work zone setting and may need more time to respond, and second, drivers may need more time in general, to react in a construction zone due to the inherent danger of construction zone areas. If the operating speed is 65 mph, (95 fps) then the next sign should be placed 1,425 feet (95 fps * 15 sec) from the first sign.

Sign Message

The message of "Do Not Pass/When Flashing", by itself, may not result in the desired driver response through the dynamic LMTCS. This system uses a familiar message of "Do Not Pass" in an unfamiliar setting created at the work zone, which requires the driver to alter his/her normal response. For example, when a "Do Not Pass" sign is posted on a two-lane roadway, the driver interprets the sign as to <u>continue to travel in the same lane and do not pass any vehicles traveling in the opposing direction</u>. "Do Not Pass" signs at a normal four-lane divided highways (2 lanes each direction) means no lane change actions due to sight distance restrictions or other potential problems. In the noted examples, drivers are familiar with the message and proper driver response. However, when the same message (Do Not Pass) is used in a manner not consistent with normal use such as being incorporated into a work zone setting, the message implies a slightly different response and some motorists may be confused and may not take the proper action, at least at the proper time.

The message “Do Not Pass/When Flashing” in work zones implies the following when the signs are activated:

1. If you are in the discontinuous lane, do not pass any vehicles in the adjacent lane and merge to the continuous lane when a reasonable gap is available
2. If you are already in the continuous lane, continue traveling in that lane

This meaning in the work zones is very different than its meaning at a permanent no passing zone location, particularly, on a typical two-lane roadway. Additional signs should be incorporated into the system, in order to precisely indicate the proper message to the driver by providing the appropriate clue.

SYSTEM DEVELOPMENT

System Layout

As a part of the Phase II study, several modifications were made to the system layout in order to address the issues discovered during the Phase I study. These modifications were based on the human factors and “Positive Guidance” analyses and included revising the signing sequence, spacing between dynamic signs and incorporating an additional illuminated changeable message sign, in order to further instruct the drivers on how to respond to the system.

In Phase II, the sequence of signs placed after the dynamic sign trailers were revised to incorporate static “Do No Pass” signs placed in between the standard lane closure warning signs (Figure 4b, page 17) and dynamic “Do Not Pass/When Flashing” signs. This signing sequence makes drivers aware that they are still in the no passing zone, while providing additional warning and regulatory signs at the critical taper area.

The spacing of the dynamic signs for the Phase II study was developed based on the time it takes for a driver to see, understand and react to a traffic sign, as well as considering travel speed. As shown in the previous section, a nominal distance of 1,500 feet was used as the spacing needed between dynamic signs and a spacing of 700 feet between all other signs was used in Phase II of the study, as shown on Figure 4b, page 17.

In order to provide an additional cue to the motorists to respond appropriately to the "Left Lane/Do Not Pass/When Flashing" signs (for a left lane closure) well in advance of lane drop area, a changeable message sign was included upstream of dynamic signing with "Merge Right" text with an arrow symbol in the Phase II study, as shown in Figure 4b (page 17). Also for Phase II study, indicator lights on the back of the trailer, indicating whether the sign is activated, were made larger to be more easily seen by the police officers from a reasonable distance.

As a part of the Phase II study, the dynamic LMTCS was implemented and tested for **right lane** closures, in addition to left lane closures. In order to guide motorists into the proper lane, sign panels with text "Right Lane/Left Lane" were mounted above the "Do Not Pass/When Flashing" signs. These additional "Left Lane" or "Right Lane" panels added to the top of the dynamic "Do Not Pass/When Flashing" signs provided a complete message of "Left Lane/Do Not Pass/When Flashing" or "Right Lane/Do Not Pass/When Flashing", to inform the motorists of the left lane or right lane closures respectively.

Sensor Settings

The dynamic LMTCS can be very helpful in reducing aggressive driver behavior and increasing safety at work zones, where lane closures are necessary. In order to utilize this system in the most efficient manner, focus must be placed on making sure that the drivers understand and realize the need for such a system. One approach to sending the appropriate message to drivers is to adjust the system based on expected traffic conditions (flow, speed, and density). The dynamic LMTCS operates with the use of sensors that have the ability to communicate with each other. It is by giving these sensors the correct input that optimum performance of the system can be achieved.

The most important parameters of the system that are manually input to the system are the **sensor detection time** and the **threshold occupancy** percent. The sensor detection time is the period of time that the sensor is monitoring the presence of traffic in the detection zone. Occupancy levels are defined as the percentage of the total monitoring period (sensor detection time) that vehicles are present in the detection zone. When the measured occupancy levels exceed the preset occupancy threshold value, a message is sent to the next upstream sign and it begins to flash. If the sensors are given improper detection time and threshold occupancy settings, the system will not operate efficiently and the desired effect of reducing aggressive driver behavior may not be achieved. Inefficiency of the system also sends confusing messages to drivers, causing some drivers to discredit and mistrust the system entirely.

In an effort to determine the optimal settings to be given as input to the sensors, a method was developed for calculating the percent occupancy based on flow (Q), speed (V), and density (K) values as a part of the Phase II study. In order to determine how occupancy is affected by varying traffic conditions, a variety of occupancy levels were generated for various levels of observed traffic flow and vehicle speeds based on the sensor readings from the dynamic lane merge trailer using a laptop computer. This allowed for the comparison of calculated occupancy values, to those measured by the sensors in the field at the southbound US-31 site in Muskegon (Phase I system layout was still in use, spring 2001).

In general, the theoretical values were higher than the actual measured values; however, they followed similar trends. The relationship between occupancy values for both the field readings and calculated values versus density for various sensor detection times are shown in Figure 5.

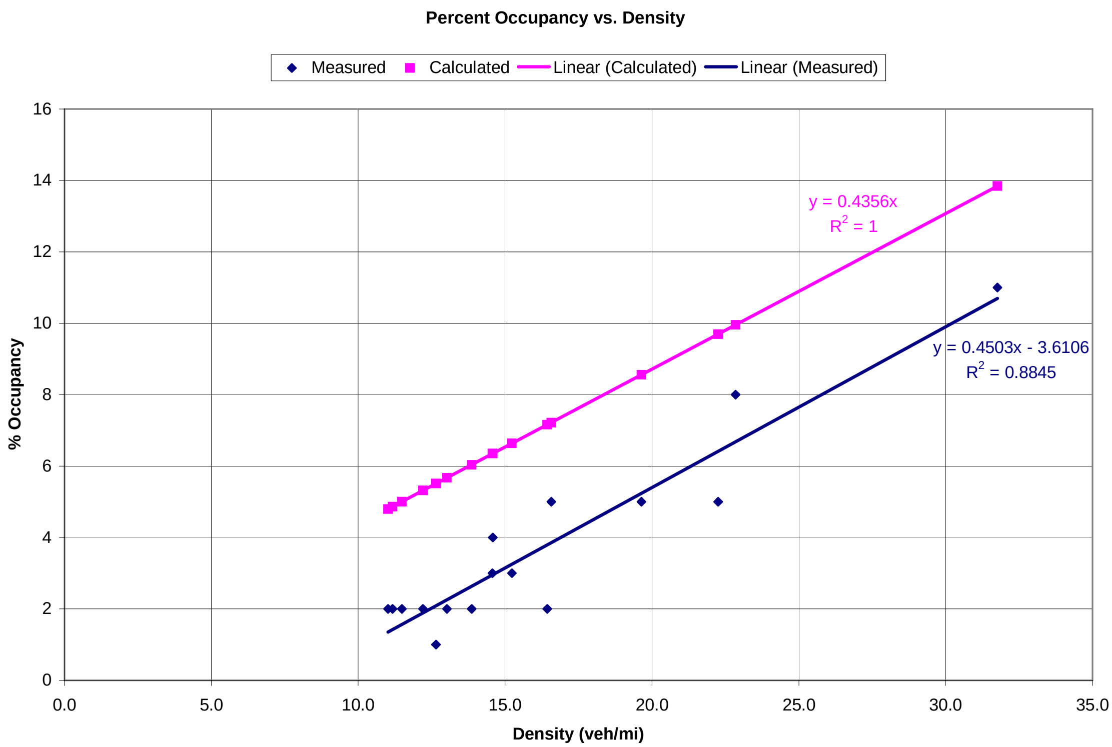


Figure 5. Relationship between Theoretical and Actual Percent Occupancies versus Density

The calculated occupancy readings as shown in Figure 5, have a linear relationship with density. This relationship is based on the equation for percent occupancy:

$$\textit{\% Occupancy} = \left(\frac{q * D}{5280 * V}\right) * 100\%$$

where:

D = total distance traveled by a vehicle while being detected by the sensors in feet which is equal to 23 feet

V = average vehicle speed in miles per hour

q = flow rate in vehicles per hour (vph)

Since density (K) in vehicles per mile is equal to flow divided by average speed (K = q/V), percent occupancy can be written as:

$$\textit{\% Occupancy} = \left(\frac{D * 100}{5280}\right) * K$$

where the quantity (D*100)/5280 is a constant and is equal to (23*100)/5280 = 0.435.

Thus, substituting (D*100/5280) with the value of 0.435 gives the equation of the line for percent occupancy as a function of density:

$$\textit{\% Occupancy} = 0.435\, K$$

The measured occupancy readings, as shown in Figure 5, also have a linear relationship with density. A regression analysis was performed in order to determine the equation of the best-fit line through the field measured percent occupancy and calculated density. This analysis resulted in the following equation:

$$\textit{\% Occupancy} = 0.4503\, K – 3.6106 \qquad \text{where the coefficient of correlation } R^2 = 0.8845$$

As a part of the field observations on US-31, various settings for threshold occupancy and sensor detection time were tested. From this, the optimal sensor detection time was determined to be one minute for each sensor. A shorter detection time makes the system too sensitive to short-term fluctuations in measured occupancy values caused by traffic platoons. This resulted in the signs being activated unnecessarily as indicated by low traffic volumes. When the sensor detection time was longer, the system was too slow in activating the upstream sign prior to the traffic queue build up.

Optimal occupancy thresholds were determined for each of the signs (signs 1 through 4) (Figure 4b, page 17), as well as for alternative scenarios, based on the location of freeway on and off ramps. For all the scenarios, it is recommended that the sensor settings vary from sign to sign to ensure that the system is more sensitive to traffic volume changes near the taper area of a work zone lane closure. According to the system design, the sign number 1 (the sign closest to the taper) is always flashing and the sensor located on the sign 1 trailer sends the message to sign 2 to activate or deactivate its flashing signal. Similarly, the sensor on the sign 2 trailer monitors vehicle occupancy and communicates with sign 3 to activate or deactivate its flashing signal. This is true for signs 3 and 4 as well. However, the sign 5 trailer is not equipped with a sensor, since it is the last dynamic sign in the series.

Since the sensor at sign 1 triggers sign 2, and queues tend to develop more rapidly near the taper, the sensor at sign 1 should be set at the highest sensitivity level. Therefore, the sensor at sign 1 is given the lowest threshold occupancy and all subsequent sensors are given increasingly higher threshold occupancy values.

The effectiveness of the dynamic LMTCS is dependant on how well the system can respond to traffic congestion in a work zone. The presence of on and off ramps influence the traffic volumes through the work zone and, if not accounted for, may affect the system's performance.

The system layout and sensor setting parameters were then implemented at the sites tested in Phase II of the study.

PHASE II TESTING OF THE MICHIGAN LMTCS

Site Description

As a part of Phase II study in the summer of 2001, the dynamic LMTCS with the revised system layout and settings were implemented at three locations:

- SB M-53 in Macomb County
- NB M-53 in Macomb County
- Westbound (WB) I-96 in Grand Rapids

Southbound M-53 site - Macomb County

The Southbound M-53 site consisted of a two-lane freeway section with a right lane closure. The lane merge traffic control system included five dynamic “Do Not Pass/When Flashing” signs, three static “Do Not Pass” signs, a changeable message sign with text “Merge Left” and an arrow symbol and various traditional construction zone warning signs.

The system layout for the SB M-53 site was similar to that shown in Figure 4b (page 17), but for a right lane closure instead of a left lane closure. One unique feature of the SB M-53 site was the presence of an interchange for a major arterial (M-59/Hall Road) located within the dynamic LMTCS. The following is a description of the entrance and exit ramps of this interchange with respect to the dynamic “Do Not Pass/When Flashing” signs:

- Two entrance ramps were located downstream of dynamic sign number 1
- One exit ramp was located immediately upstream of dynamic sign number 2

Most of the volume fluctuations, due to the M-59 interchange, were not detected by the sensors on the dynamic LMTCS due to the entrance and exit ramp locations described above. Thus, special care was taken when setting the threshold occupancy percentages that trigger the system to activate. The setting at sign number one and sign number two were set very low to ensure that the system would be able to respond to queues that accumulated quickly. The sensor settings implemented at the SB M-53 site adjusted for the entrance and exit ramp locations are as follows:

Sign No.	Threshold Occupancy	Sensor Detection Time
1	4%	1 minute
2	5%	1 minute
3	7%	1 minute
4	9%	1 minute

Two unique issues at the M-53 site resulted due to the right lane closure and the location of the entrance and exit ramps. They are as follows:

1. Typically, a no passing zone is established to prevent drivers from using the left lane to pass vehicles in the right lane. The right lane closure on M-53 required an extra “Right Lane” placard to be placed above the dynamic “Do Not Pass” sign, informing the motorists that the no passing zone was affecting the right lane.

2. The interchange of M-53 and M-59 presented another issue for drivers exiting SB M-53 freeway onto M-59. If the motorists were to respond to the changeable message sign, they would merge into the left lane and then be forced to cross the right discontinuous lane to access the M-59 exit ramp. In order to provide clarity to the motorists, the changeable message sign placed in the signing sequence with text “Merge Left with an arrow symbol” was modified to “Thru Traffic/Merge Left” with an arrow symbol, meaning that the exiting traffic can continue in the right lane.

Northbound M-53 site - Macomb County

The northbound M-53 dynamic LMTCS site was similar to the SB M-53 site studied previously. The taper of the NB site was approximately three (3) miles north of the previous SB site. Northbound M-53 is a two-lane suburban commuter highway that experiences directional flows. The NB experiences severe congestion conditions during the PM peak periods. The construction site was studied with both right lane and left lane closures separately. Initially the left lane was closed for construction, and after the construction work was finished, the right lane was closed and the taper point moved slightly more than one-quarter mile south. The taper was moved south due to an exit ramp in the area. The merge area of the site was not affected by the 23 Mile Road interchange.

Westbound I-96 site - Grand Rapids

The dynamic LMTCS site near the City of Grand Rapids was a two-lane highway that connects two large urban cities, Lansing and Grand Rapids. The highway experiences fluctuating traffic volumes with peaks in the AM and midday through evening. The area leading up to the construction zone was free of entrance and exit ramps.

The following are the AADT and peak hourly flow ranges for the Phase II sites

LOCATION	AADT- TOTAL OF BOTH DIRECTIONS OF TRAVEL (VEHICLES PER DAY)	PEAK HOUR FLOW RANGES- ONE DIRECTION OF TRAVEL (VEHICLES PER HOUR)
Macomb County M-53	46,100	2,234 – 3,051
Kent County I-96	36,200	1,064 – 2,006

Data Collection for Phase II

M-53 Sites - Macomb County

The method of data collection for Phase II was similar to that collected in Phase I. Travel time data was collected by conducting travel time runs using the floating car method. A video camera and/or manual observations were used to record traffic volume and driver actions through the lane merge area. These observations were performed concurrently with the travel time runs to capture the flow rates associated with the various travel times. Driver behavior was also monitored at the taper area. The data at the M-53 sites were collected during the peak periods, since the lane discipline is most critical during high traffic volume scenarios. For the SB M-53 site, the peak period was observed during the morning (AM Peak) and for the NB M-53 site, the peak period was observed during the evening (PM Peak).

At the M-53 sites in Macomb County, the data collection began before the dynamic LMTCS was operational. This allowed for a baseline comparison to test the effects of the dynamic LMTCS on the traffic conditions in the merge area. Thus, travel time, traffic operation and driver behavior data was collected at the work zone with lane closure at the M-53 sites.

A summary of the data collected at the NB and SB M-53 sites is presented in Table 2, both before and after the implementation of the dynamic LMTCS. The 'before' data was collected at the site with a lane closure in place using traditional signage. The 'after' data was collected at the same site with the dynamic LMTCS in place.

Table 2. Summary of Peak Period Before and After Data for (a) SB M-53 (b) NB M-53

(a) SB M-53- AM Peak Period* Traffic Operations and Characteristics

Operational and Driver Behavior Characteristics for Phase II	Before Period	After Period
Average Travel Speed Based on Peak Period Travel Time Runs (mph)	36.7 mph	40.3 mph
Average Peak Hour Delay per 10,000 feet	112 sec/veh	83 sec/veh
Average Peak Hour Flow	2061 vph	2074 vph
Average Number of Stops per Travel Time Run	1.7	0.4
Average Stopped Time Delay per Travel Time Run (sec)	46.2	4.4
Average Number of Aggressive Driving Maneuvers per hour during the peak hour	68.0	32.0
Average Length Traveled during Travel Time Runs	26,496 feet	22,057 feet

*** Two Hours: 7:00-9:00 AM**

(b) NB M-53 PM Peak Period* Traffic Operations and Characteristics

Operational and Driver Behavior Characteristics for Phase II	Before Period	After Period
Average Travel Speed Based on Peak Period Travel Time Runs (mph)	18.3mph	26.8 mph
Average Peak Hour Delay per 10,000 feet	285 sec/veh	187 sec/veh
Average Peak Hour Flow	1583 vph	1692vph
Average Number of Stops per Travel Time Run	2.4	1.5
Average Stopped Time Delay per Travel Time Run (sec)	126.5	98.1
Average Number of Aggressive Driving Maneuvers per hour during the peak hour	38.0	9.0
Average Length Traveled during Travel Time Runs	15,479 feet	14,958 feet

***Three Hours: 3:00-6:00 PM**

A comparison of the before and after data at the two M-53 test sites indicated the following:

- At similar flow rates during the 'before' and 'after' period, the average travel speed based on the peak period travel time runs, increased slightly after the implementation of the dynamic LMTCS at both the NB and SB M-53 sites.
- The average peak period travel time delay decreased during the after period at both M-53 sites.
- The average peak hour flow remained similar for the before and after periods at both the M-53 sites.
- Based on the peak hour travel time runs, the average number of stops for the NB and SB sites decreased after the implementation of the dynamic LMTCS. The average duration of the stopped time per run also decreased for both the sites in the 'after' period.

The average number of stops is an important factor of effectiveness. The acceleration and deceleration, due to a platoon of vehicles stopping, causes additional fuel consumption and produces unnecessary emissions. In addition, the average stopped time assesses the time that vehicles are idling. Typically, when vehicles are idling, carbon monoxide emissions released into the environment may contribute to air quality problems. Thus, a reduction in the number of stops and the average stopped time per run experienced in the after period, imply that the dynamic LMTCS may improve some of the negative environmental effects.

In addition, the number of aggressive driving maneuvers during the survey period for the before and after periods were compared, in order to assess the effectiveness of the system in terms of reducing safety risks. At the SB M-53 site, there was a high number of aggressive driving maneuvers during the before period with an average of 68 per hour, observed during the peak period.

It is important to note that the dynamic LMTCS was first implemented in the SB M-53 site. Prior to this installation, motorists in this area were not previously exposed to the dynamic LMTCS. After the dynamic LMTCS was implemented, the number decreased to 32 aggressive driving maneuvers per hour during the peak period (Table 2a) and police enforcement was incorporated in this project with state and local police monitoring the area on a daily basis at various times of day. The police enforcement was present to help drivers respect and comply with the system since it is new and unfamiliar to most drivers. It is expected that once drivers are accustomed to the system, only routine police enforcement will be necessary.

At the NB M-53 site, the number of aggressive driving actions was observed at 38 per hour before the installation of the dynamic LMTCS. It reduced to 9 per hour, after the system installation. Please note that during the NB M-53 before period, although the dynamic LMTCS was not installed, it appears that the system installation on the SB travel lanes had an effect on the driver behavior. A comparison of the "before" period between the NB and SB sites indicated that a lower number of aggressive driver actions (38 per hour at the NB site and 68 per hour at the SB site). This is probably due to the increased driver familiarity of the system, as well as the media exposure of the lane merge system and strict police enforcement on SB M-53.

Westbound I-96 Site - Grand Rapids, Kent County

At the WB I-96 site near the City of Grand Rapids, Kent County, travel time runs and aggressive driver maneuver data was collected after the installation of the dynamic LMTCS. It was not possible to collect ' before' data at this site, since a lane closure was not present at the work zone before the implementation of the dynamic LMTCS. The 'after' data was collected during various times of the day. Table 3 shows the operational data collected after the installation of the dynamic LMTCS.

Table 3. Summary of After Data for WB I- 96 Site in Grand Rapids

Operational and Driver Behavior Characteristics for Phase II	After Period
Average Travel Speed Based on Peak Period Travel Time Runs	44 mph
Average Peak Hour Delay	81 sec/veh
Average Peak Hour Flow	1244 vph
Average Number of Aggressive Driving Maneuvers per hour during the peak hour	1.6

The data collected for traffic operations as a part of Phase II is included in Appendix II.

STATISTICAL ANALYSIS

A statistical analysis was performed as a part of this study in order to quantify the differences in the measures of effectiveness (MOEs), which are attributable to the installation of the dynamic LMTCS. The measures of effectiveness that were evaluated included 'travel time delay' per 10,000 feet traveled.

The statistical analysis is based on a "before and after" study of the data collected at the M-53 sites, during the peak periods. In the "before and after" study plan (Figure 6) only the test sites are used and data for the MOEs are compared 'before' and 'after' the implementation of the dynamic LMTCS.

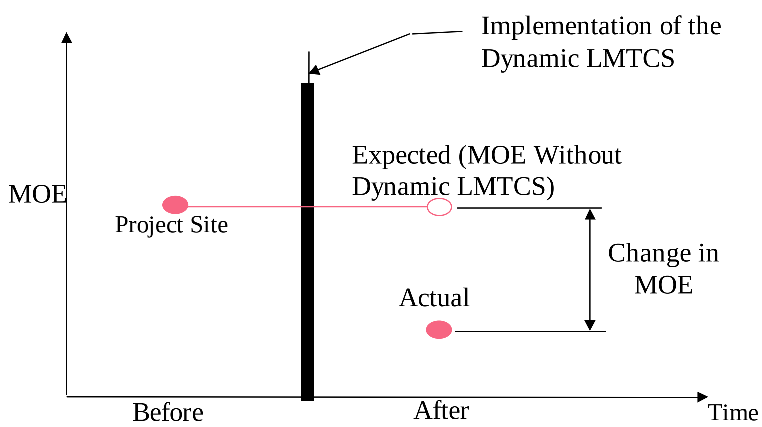


Figure 6. Before and After Evaluation Plan

The Z-test was used to test the effectiveness of the dynamic LMTCS in terms of travel time delay. The Z-test will determine if there are differences in delay, "before" and "after" the implementation of the dynamic LMTCS at work zones with lane closures. The Z-test is used when the data follows a normal distribution and the sample size is greater than 30. Since the travel time data follows a normal distribution, and the number of travel time runs for the NB and SB M-53 sites combined is 79 for the before period and 83 for the after period, the Z-test is appropriate to be used in this analysis.

The Z-test will compare the travel time data for the test sites, before and after the implementation of the dynamic LMTCS to determine if there are significant benefits of the system in terms of reducing travel time delay, thus improving traffic operations through lane closure areas.

The null and alternative hypotheses are as follows:

H_o: There is no difference in the mean travel time delay, before and after the implementation of the dynamic LMTCS

H_a: The mean travel time delay before is greater than the mean after the implementation of the dynamic LMTCS.

The Z-test statistic is as follows:

$$Z = \frac{\overline{X}_b - \overline{X}_a}{\hat{S}}$$

Where:

$\overline{X}_b$ = mean of the "before" travel time delay data for NB and SB M-53 sites combined

$\overline{X}_a$ = mean of the "after" travel time delay data for NB and SB M-53 sites combined

$\hat{S}$ = standard deviation of the difference of the means

$$= \sqrt{\frac{S_b^2}{n_b} + \frac{S_a^2}{n_a}}$$

S_b, n_b = standard deviation and number of observations in the "before" period

S_a, n_a = standard deviation and number of observations in the "after" period

The mean and standard deviation of the delay rates, based on distance traveled during the runs, were calculated for the before and after data sets for both the M-53 sites (NB and SB), and they are as follows:

	Before	**After**
Mean	211.9	143.6
Standard deviation	112.3	88.4
Sample size	79	83

∴ The calculated Z-value is = 4.30.

The critical Z-value was obtained from a standard statistical table, using an alpha value of 0.05 and a level of confidence of 95% for a one-tailed test and is equal to 1.96.

Since $Z_{calculated}$ is greater than $Z_{critical}$, the null hypothesis (H_o) is rejected. This implies that the mean travel time delay before **is significantly** greater than the mean travel time delay after the implementation of the dynamic LMTCS at a 95% level of confidence.

BENEFIT-COST ANALYSIS

A benefit-cost (B/C) analysis was performed as a part of this study in order to determine the economic effectiveness of the dynamic LMTCS in Michigan. The data for the economic analysis is based on the Phase II study at the M-53 sites. The results of the data collection and analysis performed as a part of the Phase I study was used to develop the Phase II system. For the I-96 project in Grand Rapids, it was not possible to collect 'before' data since there was **no** lane closure at the work zone before the implementation of the dynamic LMTCS.

The purpose of the dynamic LMTCS is to reduce the number of aggressive driving maneuvers, improve safety and improve traffic flow by encouraging drivers to merge 'early' in the traffic stream. The sensors on the dynamic sign trailers detect traffic flows, speed and occupancy, in order to create a dynamic no passing zone. Under high traffic volume conditions, the no passing zone will encourage drivers to merge well in advance of the lane taper where larger gaps are available in the traffic stream, and will provide safe and smooth merging of traffic. This system also induces a lower differential in vehicle speeds between the two lanes, which also contributes to safety benefits. Thus, the total benefits of the dynamic LMTCS include both tangible measures such as reduced travel time and intangible measures, such as safety benefits related to a reduction in aggressive driver maneuvers and associated risk due to road rage and others.

In the economic analysis, the benefit was considered as the travel time savings due to the installation of the dynamic LMTCS in this analysis. The travel time savings were calculated as the difference between the delay recorded from the travel time runs from the 'before' and 'after' periods. The travel time saving is then converted to a monetary value by assuming a monetary equivalence for 'value of time'. The 'value of time' may be estimated according to the 'willingness to pay' or 'cost of time' concepts *(8)*. The willingness to pay concept considers what monetary value motorists would be willing to pay for travel time savings. The cost of time concept is the actual cost of providing time savings for a project. In this analysis, various values of time were used to determine the benefits due to travel time savings. The resulting benefit to cost ratios were then calculated and presented on a graph showing the B/C ratio versus value of time.

The cost of the system was considered as the cost of the system's implementation, operation and relocation, if necessary. For the M-53 sites, the dynamic LMTCS was operational for a total of 21 weeks: 6 weeks for SB M-53 and 15 weeks for NB M-53 site. This project included 5 dynamic signs, 2 changeable message signs and the relocation of these items, for a cost of the dynamic LMTCS of $48,407.80. In addition, MDOT paid for the police enforcement services of the Michigan State Police (MSP) which totaled $3,563.85. Therefore, the total cost component used in the economic analysis includes the system cost and the police enforcement cost, for a total of $51,971.65.

The travel time savings in vehicle-hours for the M-53 site was calculated as follows:

= ($Delay_{before}$ – $Delay_{after}$) (sec/veh/10,000 feet traveled) * (1/3600) (hr/sec) * (Average flow) (veh/hr) * (no. of peak hours/day) * (5 weekdays/week) * (No. weeks dynamic LMTCS was installed)

Southbound M-53 dynamic LMTCS (duration = 6 weeks)

= (112 – 83) (sec/veh/10,000 feet traveled) * (1/3600) (hr/sec) * [(2,061+2,074)/2] (veh/hr) * (2 peak hrs /day) * (5 weekdays/week) * (6 weeks)

= 999 total vehicle-hours of travel time savings per 10,000 feet traveled (based on the peak period for the entire 6 week period)

Northbound M-53 dynamic LMTCS (duration = 15 weeks)

= (285 – 187) (sec/veh/10,000 feet traveled) * (1/3600) (hr/sec) * [(1,583+1,692)/2] (veh/hr) * (3 peak hrs /day) * (5 weekdays/week) * (15 weeks)

= 10,030 total vehicle-hours of travel time savings per 10,000 feet traveled (based on the peak period for the entire 15 week period)

Total M-53 Project

= 999+ 10,030 = **11,029 total vehicle-hours** of travel time savings per 10,000 feet traveled (based on the peak period for the entire 21 week period)

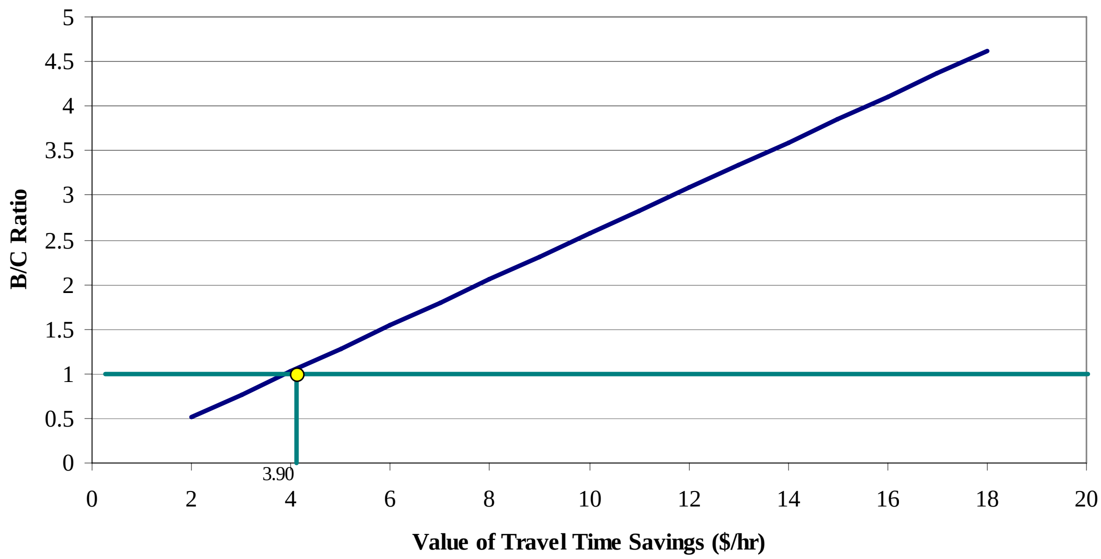
Please note that these values may also be converted to person-hours of travel time savings, considering the average vehicle occupancy to be 1.25 persons per vehicle. This would result in a total travel time savings in **total person hours of 13,786** (= 11,029*1.25).

The following table shows the monetary benefits of the dynamic LMTCS, based on various amounts of value of travel time savings in person hours.

Value of travel time savings ($/hr/person)	**Monetary Benefits of Dynamic LMTCS ($)**
$4.00	$55,144.00
$5.00	$68,930.00
$6.00	$82,716.00
$7.00	$96,502.00
$8.00	$110,288.00
$9.00	$124,074.00
$10.00	$137,860.00
$11.00	$151,646.00
$12.00	$165,432.00
$13.00	$179,218.00
$14.00	$193,004.00
$15.00	$206,790.00
$16.00	$220,576.00
$17.00	$234,362.00
$18.00	$248,148.00

The B/C ratios were then calculated based on these values of the benefits. It is important to note that since the dynamic LMTCS was implemented for a short duration of time (less than a year), the economic analysis was calculated as the direct ratio of the benefits over the costs. No projections were made to advance the costs and benefits into the future using discount interest rates, since the time frame for the economic analysis is less than a year.

The results of the B/C analysis were then plotted on a graph showing the B/C ratios versus the various values of time, as shown below:



This graph shows that for a value of time greater than $3.80, the B/C ratio will be greater than one, indicating that the monetary **benefits** of the system **outweigh** the **cost** of the system.

In a study conducted by Purdue University for the Indiana Department of Transportation regarding the safety benefits of the LMTCS suggested the use of "a delay cost of $8/hr and an average occupancy of 1.25 persons/vehicle."*(9)*

As a part of the Phase I and Phase II study, MDOT retained the services of the Michigan State Police to enforce the no passing zone created by the dynamic LMTCS. Since most drivers are initially not familiar with this system, police enforcement was present at the test sites to ensure that drivers were obeying the no passing zone. The following are the costs paid by MDOT for the police enforcement:

TEST SITE LOCATION	ENFORCEMENT COST PAID ($)	ENFORCEMENT DURATION (MONTHS)
US-27 near Grayling	$3,420.49	4 months
I-69 in Branch County	$3,000.00	6 months
US-31 in Muskegon	$18,000.00- $22,000.00	4 months
M-53 in Macomb County	$3,563.85	4 months
I-96 in Grand Rapids, Kent County	$2,000.00	

In addition to the State police enforcement, many local police departments patrolled the work zones with the dynamic LMTCS in their jurisdiction at no expense to MDOT.

The police enforcement efforts were effective in terms of educating the motorists of the *no passing in work zones* law and the dynamic LMTCS, as well as ensuring driver compliance with the dynamic LMTCS. In many instances, the police officers just gave warnings to motorists that unintentionally violated the no passing zone due to the unfamiliarity of the system.

In addition, media exposure was also found to be very effective in educating the motorists of the dynamic LMTCS, which is critical to the success of the dynamic LMTCS. These campaigns stressed the potential risk of aggressive driving in work zones and associated hazards due to road rage, as well as the importance of safe and courteous driving through these zones. This media exposure of the dynamic LMTCS also contributed to increased driver knowledge of work zone safety, which may be considered as an intangible benefit.

At many of the test sites, the number of aggressive driver maneuvers were reduced drastically from the ‘before’ to the ‘after’ periods. The reduction of aggressive driver maneuvers has a great impact on safety in the work zones in terms of traffic crash reductions, and should be considered as a critical benefit of the dynamic LMTCS. An aggressive driver maneuver in this study was considered as the action of a driver who continued to travel in the discontinuous lane up to the point where a lane change became difficult, risky and have potential of causing a safety hazard. This aggressive driving behavior creates shock waves in the traffic stream and may also induce road rage. Road rage not only exists at the lane taper area, but may also escalate while travelling within and even far beyond the work zone, creating a potentially dangerous situation. Thus, although the benefits due to the reduction in aggressive driving maneuvers cannot be related to reductions in traffic crashes due to limited applications, it certainly has a critical effect on the success of the dynamic LMTCS.

Traffic crash data was not directly used to assess the safety benefits for the two following reasons:

- time frame for analysis is too small to determine a significant finding
- lack of available data

In safety analyses, traffic crash data is collected for a two-to three year time period before the installation of a safety improvement at a location or have numerous similar site applications and compare it with two to three years crash data after the installation at a location or have numerous similar site applications. Traffic crashes are random events, which are also considered rare events. When the time frame for analysis is only based on a few months, a sound evaluation cannot be performed. The probability of a traffic crash occurring in a small time period is low, and thus, it is not possible to identify whether changes in the number of traffic crashes are due to the installation of a safety measure, or due to chance.

As a part of this project, traffic crashes would have to be obtained for the time period with the work zones were set up, both before and after the implementation of the dynamic LMTCS. In most cases the dynamic LMTCS was set up at the same time as the work zone with lane closure, or, at most, a few weeks after. Thus, a “before and after” evaluation of the traffic crash data would not provide meaningful results.

Additionally, for the M-53 sites, the construction activities were completed in mid November, and the dynamic LMTCS was removed. When obtaining traffic crash data, there is usually a one to two month time lag between the occurrence of the crash and when the traffic crash data is available. Thus, it was not possible to obtain the data for inclusion in this study.

CONCLUSIONS

The conclusions of the dynamic LMTCS tested in Michigan are as follows:

1. The dynamic LMTCS can be very helpful in reducing aggressive driver behavior, increasing safety and reducing delay at work zones where lane closures are necessary.

2. In order to utilize this system in the most efficient manner, focus must be placed on making sure that the driver understands and realizes the need for such a system. One approach to sending the appropriate message to drivers is to adjust the system based on expected traffic conditions (flow, speed, and density) in relation to the system settings and signing layout. The refinement of sensor settings, sign spacing and sign placement strategies developed as a part of this project, allowed for a more effective use of the dynamic LMTCS in Michigan.

3. The results of the Phase I study indicated that motorists may not have understood the sign message of "Do Not Pass/When Flashing", since many drivers were observed passing other vehicles through the series of flashing signs.

4. The data collection and analysis performed as a part of the Phase I efforts did not reveal any significant findings with respect to travel time and delay, which may possibly have been due to the non-optimal system settings and layout plan. However, the following observations were noted:
   - More aggressive driver behavior was observed at the static LMTCS than the dynamic LMTCS for similar flow rates.
   - Police enforcement had a positive impact on reducing the amount of aggressive driver behavior in the work zones.
   - Drivers may have been confused by the dynamic LMTCS due to the non-optimal system layout and often arbitrary sensor settings.

5. As a part of the Phase II study, several modifications were made to the system layout in order to address the issues discovered during the Phase I study. These modifications were based on the human factors and "Positive Guidance" analyses and included revising the signing sequence, spacing between dynamic signs and incorporating an additional illuminated sign in order to further instruct the drivers on how to respond to the system. The following are the modifications that were made to the dynamic LMTCS:
    - The sequence of signs placed after the dynamic sign trailers were changed to incorporate static "Do Not Pass" signs placed in between the standard lane closure warning and dynamic "Do Not Pass/When Flashing" signs.
    - The spacing of the dynamic signs was increased from 700 feet to 1,500 feet.
    - A changeable message sign was placed upstream of dynamic signing with "Merge Right" or "Merge Left" text with an arrow symbol to provide motorists with additional cues on how to respond to the system and where to merge to the open through lane.
    - In order to implement right lane closures, as opposed to only left lane closures, sign panels with text "Right Lane/Left Lane" were mounted above the "Do Not Pass/When Flashing" signs to inform motorists of the left lane or right lane closures respectively.

6. During Phase II, data collection and analysis of the sensor settings were performed in order to determine optimal values. The parameters studied included threshold percent occupancy and sensor detection time. Values for these parameters were calculated and tested in the field. Analyses were then performed to determine optimal sensor settings. These values were then tested and refined as a part of the Phase II data collection.

7. A 'before and after' study was performed for the M-53 construction project in Macomb County. The data collection and analysis performed at the M-53 sites revealed that the dynamic LMTCS was effective in improving the traffic operations and reducing safety risks through the work zone. The following are some specific findings:

- At similar flow rates during the ‘before’ and ‘after’ period, the average travel speed based on the peak period travel time runs increased slightly after the implementation of the dynamic LMTCS at both the NB and SB M-53 sites.
- The average peak period travel time delay decreased with the dynamic LMTCS at both M-53 sites.
- The average peak hour flow remained similar for construction zones with and without the dynamic LMTCS at both the M-53 sites.
- Based on the peak hour travel time runs, the average number of stops in the construction zone for the NB and SB sites decreased with the implementation of the dynamic LMTCS. The average duration of the stopped time delay per run, also decreased for both the sites when equipped with the dynamic LMTCS.
- The number of aggressive driver maneuvers during the peak hours reduced dramatically at both the NB and SB M-53 sites.

8. The results of a statistical analyses of the mean travel time delay data, indicated that the mean delay “before” was significantly higher than the mean delay “after” the implementation of the dynamic LMTCS.

9. The results of the economic analysis performed as a part of this study (based on one test site) indicated that the dynamic LMTCS will be economically beneficial and achieve B/C ratios greater than one, if a value of time of $3.80 per person hour is assumed for travel time savings.

RECOMMENDATIONS

The recommendation for future implementation of the dynamic LMTCS in Michigan is as follows:

1. The dynamic LMTCS can be implemented on highways with two lanes in each direction reduced to one lane during construction. The dynamic LMTCS may also be considered for three lane highways reduced to two lanes at freeway work zones. However, additional

signing may be necessary to inform/instruct motorists how to respond to the system. It is important to note that a pilot study may be necessary to determine the effectiveness of the work zone scenario of three lanes reduced to two lanes. Such pilot study should determine the criteria for LMTCS applications.

2. The dynamic LMTCS can be implemented at work zones with or without an interchange, including entrance and exit ramps in the immediate vicinity of the work zone. If interchanges are located within the work zone, care should be taken to ensure that the sensor settings are properly designed to respond to fluctuations in traffic. Guidelines for the sensor settings are included in Appendix III for seven different scenarios for entrance and exit ramp locations. However, these settings should be monitored in the field to verify that the system is operating efficiently.

3. The dynamic LMTCS can be used at stationary construction projects, such as bridge repair/rehabilitation, such as repaving or repair of long highway segments. If the construction activity includes relocation of the system, then pay items should be included in the construction contract for the re-location and the implementation of the lane merge traffic control system. Relocations of the system should be kept to a minimum, possibly one to two per project. If the relocations of the dynamic LMTCS are included project, the construction specification should include the availability of a work site traffic supervisor (WTS) knowledgeable about the dynamic LMTCS. The system is **not** designed to be set up and taken down on a daily or weekly basis. It is important to note that the set up and calibration of the system takes 3-5 hours for each system move.

4. The construction zone must be in place during the peak hours of travel. The dynamic LMTCS is recommended for highway projects that experience moderate to high traffic volumes prior to construction. Guidelines for implementing the dynamic LMTCS based on AADT and peak hour volumes were developed based on an analyses of expected delay using the Highway Capacity Software, as well as the traffic flow and system performance observed at the test sites. The guidelines (two lanes to one lane) are as follows:

- Directional AADT: **21,500 to 34,500 vehicles per day** per direction
- Average weekday AM and/or PM peak period volumes prior to construction (2 peak hours per day): **2,000 to 3,000 vehicles per hour** per direction

Estimated guidelines for using the LMTCS for a lane closure of three lanes reduced to two lanes are as follows:

- Directional AADT: **34,500 to 48,500 vehicles per day** per direction
- Average weekday AM and/or PM peak period volumes prior to construction (2 peak hours per day): **3,000 to 4,500 vehicles per hour** per direction

The criteria for three lanes to two lanes work zone should be tested and refined by further field study.

Please note that during construction, the traffic volumes may slightly reduce since some drivers may choose to travel on alternate routes to avoid the work zone. Thus, the traffic volume guidelines presented are for the pre-construction traffic volumes observed on a typical day.

5. The implementation of the dynamic LMTCS will be effective for projects with short and long term durations. As per conversations with equipment suppliers, if the system is implemented at short term projects (less than three week duration), the cost of implementing and operating the system will be reduced. If the system is implemented for long term projects, the system may have to be relocated and will be associated with higher implementation and continuous maintenance costs.

6. The dynamic LMTCS may be implemented when closing either the left lane or right lane in a work zone. For a right lane closure, an additional "Right Lane" or "Left Lane" sign panel (depending on which lane is closing) should be added to the dynamic sign trailer.

7. The recommended layout for the dynamic LMTCS is shown in Figure 7. This layout includes five dynamic sign trailers and a changeable message sign with text "Merge Right" (or Left) with an arrow symbol.

8. A media campaign should be accompanied with the implementation of the dynamic LMTCS in order to educate the motoring public to the benefits of the system, the changes in the law which prohibits passing in work zones with lane closures, the risk of aggressive driving in work zones and the dangers of provoking road rage.

9. When implementing the dynamic LMTCS in areas where drivers may not be familiar with the system, police enforcement should be included in order to inform/warn drivers that are unintentionally violating the no passing zone, as well as, ticketing those drivers that are blatantly disobeying the law. It is expected that once the system gains considerable familiarity, such aggressive police enforcement and educational efforts by the police may not be necessary.

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APPENDIX I- SUMMARY OF DATA COLLECTED FOR THE PHASE I STUDY

APPENDIX II- SUMMARY OF DATA COLLECTED FOR THE PHASE II STUDY

APPENDIX III- SENSOR SETTINGS FOR THE DYNAMIC LMTCS

SENSOR SETTING FOR THE DYNAMIC LMTCS FOR VARIOUS SCENARIOS

The optimal occupancy threshold values for sign nos. 1 through 4 were determined for the following seven scenarios:

1) No Ramp Located Within Work Zones
2) On ramp located between the taper and sign 1
3) On ramp located between sign 1 and sign 2
4) On ramp located between sign 2 and sign 3
5) Off ramp located between the taper and sign 1
6) Off ramp located between sign 1 and sign 2
7) Off ramp located between sign 2 and sign 3

For all the scenarios, it is recommended that the sensor settings vary from sign to sign to ensure that the system is more sensitive to traffic volume changes near the taper area of a work zone lane closure. Please note that sign number 1 is always flashing and the sensor located on the sign 1 trailer sends the message to sign 2 to activate or deactivate its flashing signal. Similarly, the sensor on the sign 2 trailer monitors vehicle occupancy and communicates with sign 3 to activate or deactivate its signal. This is true for signs 3 and 4 as well. However, sign 5 trailer is not equipped with a sensor since it is the last dynamic sign in the series.

Since the sensor at sign 1 triggers sign 2, and queues tend to develop more rapidly near the taper, the sensor at sign 1 should be set at the highest sensitivity level. Therefore, the sensor at sign 1 is given the lowest threshold occupancy and all subsequent sensors are given increasingly higher threshold occupancy values.

As a part of Phase II, the system was revised to ensure that the sensors turn on and turn off the flashing signal in sequential order. Please note that the system did not operate in this manner during Phase I; the dynamic signs were activated and deactivated independently.

For example, in the revised dynamic LMTCS in Phase II, sign no. 3 cannot become activated unless sign no. 2 is activated, regardless of the percent occupancy value detected by the sensor. This is also true for sign no. 4 and 5. Similarly, a sign cannot become deactivated unless the sign ahead is deactivated. The system was modified in the Spring of 2001 to allow the signs to continuously communicate to one another and make decisions whether to activate or deactivate the dynamic sign's flashing signal, based on:

- monitored occupancy readings, **and**
- the status (flashing or not flashing) of the nearby dynamic signs

Thus, the system was modified to ensure that the dynamic signs will not flash out of sequence.

Scenario 1: No Ramps Located Within Work Zones

The settings for **threshold occupancy** must account for sudden changes in traffic conditions. If threshold occupancies are set too low, the signs will be flashing during periods of low traffic volume conditions. However, if the settings are too high, signs will not be flashing when traffic volumes and occupancy levels are high. Table 1, shown below, lists the recommended settings for the sensors at each sign. It also shows the recommended threshold occupancy values and sensor detection times for a freeway work zone with no ramps located in the near vicinity.

Table 1: Scenario 1 (No Ramps Within the Work Zone)

Sensor at Sign No.	Threshold Occupancy (%)	Sensor Detection Time (min)
1	5	1
2	7	1
3	9	1
4	11	1

Scenarios 2-4: On Ramps Located Within Work Zone area and Dynamic LMTCS

The following are three possible scenarios when on ramps are located within the work zone area and the dynamic LMTCS:

Scenario 2: On ramp located between the taper and sign 1

Scenario 3: On ramp located between sign 1 and sign 2

Scenario 4: On ramp located between sign 2 and sign 3

Under these scenarios, the on ramps located in the near vicinity of the work zone will involve additional traffic which enters the freeway at the ramp. This traffic will result in higher density and may cause sudden queues to build up, especially when they are located near the lane taper (Scenario 2). In such instances, it is recommended that the sensor settings at each sign be reduced to provide increased sensitivity. The increased sensitivity of the sensors will allow the system to respond appropriately to rapid changes in traffic volume and occupancy. If the on ramp traffic is heavy enough to cause freeway congestion, the system must be able to detect this quickly in order to alert drivers well in advance of the queue build up. Additionally, the signs should not be flashing during periods of low traffic volumes and density conditions. This may lead to driver non-compliance to the dynamic LMTCS since drivers may perceive the system to be ineffective. The recommended settings, as shown in Tables 2, 3 and 4 are given for on ramps located at various locations throughout the work zone.

Table 2: Scenario 2 (On Ramp Between Taper and Sign 1)

Sensor at Sign No.	Threshold Occupancy (%)	Sensor Detection Time (min)
1	4	1
2	5	1
3	7	1
4	9	1

Table 3: Scenario 3 (On Ramp Between Signs 1 and 2)

Sensor at Sign No.	Threshold Occupancy (%)	Sensor Detection Time (min)
1	5	1
2	5	1
3	7	1
4	9	1

Table 4: Scenario 4 (On Ramp Between Signs 2 and 3)

Sensor at Sign No.	Threshold Occupancy (%)	Sensor Detection Time (min)
1	5	1
2	5	1
3	5	1
4	7	1

The above settings should have the ability to detect rapid changes in traffic conditions due to additional incoming traffic from the on ramps.

Scenarios 5-7: Off Ramps Located Within Work Zone Areas and Dynamic LMTCS

The following are three possible scenarios when off ramps are located within the work zone area and the dynamic LMTCS:

Scenario 5: Off ramp located between the taper and sign 1

Scenario 6: Off ramp located between sign 1 and sign 2

Scenario 7: Off ramp located between sign 2 and sign 3

When off ramps are located in the near vicinity of the work zone, traffic volumes in the dynamic LMTCS will vary from location to location. The traffic volumes will be lighter downstream of the exit, and heavier upstream of the exit. To ensure that the system responds appropriately, or at all, to these variations in traffic flow, it is recommended that the sensor settings have a higher sensitivity for the signs located downstream of the off ramp. It is important to note that since the dynamic LMTCS was revised to trigger the signs sequentially, the threshold occupancies for the signs located downstream of the off ramp **must be set low** or else the entire system will not be activated.

Tables 5 through 7 list the recommended sensor settings for situations where an off ramp is located within the dynamic LMTCS

Table 5: Scenario 5 (Off Ramp Between Taper and Sign 1)

Sensor at Sign No.	Threshold Occupancy (%)	Sensor Detection Time (min)
1	5	1
2	6	1
3	7	1
4	9	1

Table 6: Scenario 6 (Off Ramp Between Signs 1 and 2)

Sensor at Sign No.	Threshold Occupancy (%)	Sensor Detection Time (min)
1	4	1
2	5	1
3	7	1
4	9	1

Table 7: Scenario 7 (Off Ramp Between Signs 2 and 3)

Sensor at Sign No.	Threshold Occupancy (%)	Sensor Detection Time (min)
1	4	1
2	5	1
3	5	1
4	7	1