EVALUATION OF SAFETY AND OPERATIONAL EFFECTIVENESS OF DYNAMIC LANE MERGE SYSTEM IN FLORIDA

Contract No: BD 548-24

FINAL REPORT

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April, 2009

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1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Evaluation of Safety and Operational Effectiveness of Dynamic Lane Merge System in Florida		5. Report Date April, 2009 6. Performing Organization Code 1650719
7. Author(s) Essam Radwan, Ph.D., P.E.; Rami Harb and Shankar Ramasamy, P.E.		8. Performing Organization Report No.
9. Performing Organization Name and Address University of Central Florida 4000 Central Fl Blvd, Orlando, FL 32816		10. Work Unit No. (TRAIS) 11. Contract or Grant No. BD 548-24
12. Sponsoring Agency Name and Address Florida Department of Transportation 605 Suwannee St. MS 30 Tallahassee, Florida 32399 (850)414-4615		13. Type of Report and Period Covered Final Report 14. Sponsoring Agency Code
15. Supplementary Notes		

16. Abstract

The Florida Department of Transportation (FDOT) addressed their interest in incorporating and testing an ITS-based lane management system into their existing Maintenance Of Traffic (MOT) plans for short term movable work zones (e.g. milling and resurfacing jobs). Two forms of lane merging namely the early merge and the late merge were designed to advise drivers on definite merging locations. Previous dynamic lane merging systems comprise several Portable Changeable Message Signs (or other forms of dynamic message signs) and traffic sensors. The addition of multiple PCMSs to the current FDOT MOT plans may encumber the latter. Moreover, previously deployed DLM systems (dynamic early merge systems and dynamic late merge systems) may require relatively extensive equipment installation and relocation which could be inefficient for short term movable work zones (moving on average every 7 to 10 hours). Therefore, two Simplified Dynamic Lane Merging Systems (SDLMS) are suggested for deployment and testing on short term work zones. The first SDLMS is a simplified dynamic early merge system (early SDLMS) and the second SDLMS is a simplified dynamic late merge system (late SDLMS). The following chapters elaborate further on the two suggested forms of the SDLMS. This study aims at comparing the effectiveness of both forms of SDLMS to the conventional MOT plans deployed by FDOT.

17. Key Word Work zone, Dynamic early merge, Dynamic late merge		18. Distribution Statement No Restriction	
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 78	22. Price

ACKNOWLEDGEMENTS

The authors would like to thank the Florida Department of Transportation for supporting and funding this research. The authors also express their gratitude to Sastry Putcha, Stefanie Maxwell, and Cheryl Adams for their constant support and constructive contribution and suggestions. We also would like to thank IRD Inc., Smart Traffic Systems LLC, Ranger Construction and Archer Western Contractors Ltd. for their help and support in data collection.

EXECUTIVE SUMMARY

Traffic safety and efficiency of roadway work zones have been considered to be one of the major concerns in highway traffic safety and operations in Florida. The Florida Department of Transportation (FDOT) addressed their interest in incorporating and testing an ITS-based lane management system into their existing Maintenance of Traffic (MOT) plans for short term movable work zones (e.g. milling and resurfacing jobs). Two forms of lane merging namely the early merge and the late merge were designed to advise drivers on definite merging locations. Previous Dynamic Lane Merging (DLM) systems comprise several Portable Changeable Message Signs (PCMS) and traffic sensors. The addition of multiple PCMSs to the current FDOT MOT plans may encumber the latter. Moreover, previously deployed DLM systems (dynamic early merge systems and dynamic late merge systems) may require relatively extensive equipment installation and relocation which could be inefficient for short term movable work zones (moving on average every 7 to 10 hours). Therefore, two Simplified Dynamic Lane Merging Systems (SDLMS) were deployed and tested on short term work zones. The first SDLMS is a simplified dynamic early merge system (early SDLMS) and the second SDLMS is a simplified dynamic late merge system (late SDLMS). Both SDLMS consisted of supplementing the Motorists Awareness System (MAS) MOT plans used in Florida work zones with an ITS-based lane management system.

The SDLMS system was deployed and tested at two sites in Florida. For the first site, the capacity of the work zone and the travel time through the work zone under the control (MAS) and test MOT plans (early and late SDLMS) were compared. As for the second site, data was collected extensively which enabled us to compare safety and operational Measures of Effectiveness (MOE) under different demand volumes. The temporal speed fluctuation at the location of the Remote Traffic Microwave Sensor (RTMS) of the work zone and the capacity of the work zone under the control (MAS) and test MOT plans (early and late SDLMS) were compared. Results from both sites showed that the early and late SDLMS have the potential to enhance safety as well as operations in Florida work zones. The early and late SDLMS performed better than the regular MAS MOT plan. Evaluating safety and operational measures of effectiveness, we concluded based on the two sites that the early SDLMS performs best under low volumes and the late SDLMS performs best under heavier volumes.

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LIST OF ACRONYMS

DLM - Dynamic Lane Merge
FDOT - Florida Department of Transportation
MAS - Motorists Awareness System
MOE - Measures of Effectiveness
MOT - Maintenance of Traffic
MUTCD - Manual on Uniform Traffic Control Devices
PCMS - Portable Changeable Message Signs
PRS - Portable Regulatory Signs
RSDU - Radar Speed Display Unit
RTMS - Remote Traffic Microwave Sensor
SDLMS - Simplified Dynamic Lane Merging Systems
SWZ - Smart Work Zones
UCF - University of Central Florida

1. INTRODUCTION

1.1. Work Zone Issues

Traffic safety and efficiency of roadway work zones have been considered to be one of the major concerns in highway traffic operations in Florida. Due to the capacity reduction which is the result of lane closure in work zone area, congestion will occur with a high traffic demand. The congestion will increase number and severity of traffic conflicts which raises the potential for accidents and meanwhile traffic operational properties of roadway in work zone area will also be deteriorated.

1.2. Work Zone Lane Management Schemes

To improve traffic safety and mobility in work zone areas, the DLM system, an intelligent work zone traffic control system, has been introduced in several states of the U.S. The DLM can take two forms; dynamic early merge and dynamic late merge. The dynamic aspect of the DLM systems allow them to respond to real-time traffic changes via traffic sensors. The idea behind the dynamic early merge is to create a dynamic no-passing zone to encourage drivers to merge into the open lane before reaching the end of a queue and to prohibit them from using the closed lane to pass vehicles in the queue and merge into the open lane ahead of them *(70)*. A typical early merge DLM system consists of queue detectors and "DO NOT PASS WHEN FLASHING" signs that would be triggered by the queue detectors. When a queue is detected next to a sign, the next closest sign's flashing strobes, upstream, are activated creating the no-passing zone *(71)*.

The concept behind late merge is to make more efficient use of roadway storage space by allowing drivers to use all available traffic lanes to the merge point. Once the merge point is reached, the drivers in each lane take turns proceeding through the work zone *(50)*. A typical dynamic late merge system consists of several PCMSs that would be activated under certain traffic conditions to display "USE BOTH LANES TO MERGE POINT" and a PCMS at the taper advising drivers to "TAKE TURNS / MERGE HERE". In contrast to the static lane merging, the DLM systems respond to real-time traffic changes via traffic sensors. The real-time traffic data acquired by the sensors are communicated to a central controller in a time-stamped manner. Appropriate algorithms determine whether to activate real-time lane merging messages to drivers based on preset traffic characteristics thresholds.

1.3. Research Motivation

The FDOT addressed their interest in incorporating and testing an ITS-based lane management system into their existing MOT plans for short term movable work zones (e.g. milling and resurfacing jobs). As mentioned, the two forms of lane merging namely the early merge and the late merge were designed to advise drivers on definite merging locations. Previous dynamic lane merging systems comprise several PCMS (or other forms of dynamic message signs) and traffic sensors. The addition of multiple PCMSs to the current FDOT MOT plans may encumber the latter. Moreover, previously deployed DLM systems (dynamic early merge systems and dynamic late merge systems) may require relatively extensive equipment installation and relocation which could be inefficient for short term movable work zones (moving on average every 7 to 10 hours). Therefore, two SDLMS are suggested for deployment and testing on short term work zones. The first SDLMS is a simplified dynamic early merge system (early SDLMS) and the second SDLMS is a simplified dynamic late merge system (late SDLMS). The following chapters elaborate further on the two suggested forms of the SDLMS. This study aims at comparing the effectiveness of both forms of SDLMS to the conventional MOT plans deployed by FDOT.

1.4. Research Objectives

The main objective of this research was to evaluate safety and operational effectiveness of the two proposed SDLMS systems in the field. Recommendations on the system effectiveness were provided. The objectives of this project can be summarized as the following:

1. Propose a scheme for the field test including the DLM system configuration and the approach for data collection.

2. Compare safety and operational MOE between with and without SDLMS (early and late) system in work zone areas for various traffic settings.

3. Provide field observations and recommendations regarding the system implementation.

4. Provide a preliminary guideline on how and when the SDLMS (early or late) system is warranted.

2. LITERATURE REVIEW

2.1. Safety and Operational Concerns at Work Zones

The first section of the literature review presents a synopsis of work zones safety aspects including crash rates, crash severity, contributing factors, crash types, and traditional safety countermeasures deployed in work zones. This section also exposes the road geometry, environment, and vehicle factors affecting work zone capacity.

2.1.1. Crash Rates at Work Zones

According to the Fatality Reporting System (FARS), Florida fatal work zone crashes seemed to have increased since 1999 due to the modification of the crash reporting system in 2002 *(18)*. Several studies were undertaken to assess the safety of highway construction zones in numerous states of the United States. These studies corroborate that work zones produce a significantly higher rate of crashes under certain conditions when compared to non-work zone locations. In particular, Hall and Lorenz *(34)* stated that work zones are responsible for a 26% increase in motor vehicle crashes during construction or roadway maintenance. Moreover, Rouphail et al. *(67)*, Garber and Woo *(26)*, Nemeth and Migletz *(54)*, Pigman and Agent *(62)*, Zhao *(77)*, Pal and Sinha *(59)*, Garber and Zhao *(28)* and Khattak and Council *(42)* investigated crash rates at work zone and concluded that under certain conditions work zones generate significantly higher rates of crashes compared to non-work zone locations. Pratt et al. *(64)* analyzed workers fatalities in American highway work zones between 1992 and 1998 and underlined the need to mitigate workers risk at work zones. Gundy *(32)* presented a review of existing empirical studies and literature concerning work zone traffic accidents, and concluded that accident rates in work zones are higher than similar non-work zone locations. Table 2.1 summarizes the studies' results concerning crash rates.

Table 2.1: Summary of Studies' Results Concerning Crash Rates

SUBJECT	STUDIES	RESULTS
Crash Rates	Hall and Lorenz *(34)* Rouphail et al. *(67)* Garber and Woo *(26)* Nemeth and Migletz *(54)* Pigman and Agent *(62)* Gundy *(32)* Pratt et al. *(64)* Zhao *(77)* Pal and Sinha *(59)* Garber and Zhao *(28)* Khattak and Council. *(42)*	Work zones produce significantly **more** crashes than non-work zones

2.1.2. Crash Severity at Work Zones

The severity of crashes at work zone locations was compared to the severity of crashes at non-work zone locations by several studies. However, the findings of these studies were inconsistent. Ha and Nemeth *(33)*, Nemeth and Migletz *(54)*, Nemeth and Rathi *(55)*, and Rouphail et al. *(67)* stated that work zone crashes were "to some extent" less severe than non-work zone crashes. On the other hand, Pigman and Agent *(62)* and Summary Report on Work Zone Accidents *(69)* reported that work zone crashes are more severe than non-work zone crashes. Moreover, Hall and Lorenz *(34)* and Garber and Woo *(26)* stated that there is no significant statistical difference between the crash severity at work zone and non work zone locations. Another study by Hargroves *(36)* indicated that the average work zone crash was slightly more severe than non-work zone crashes in terms of the average property damage and the number vehicles involved in the crash. This study also concluded that the average work zone crash was slightly less severe than non-work zone crashes in terms of property damage only crashes and the number of people injured or killed in the accident. Zhao *(77)* specified that 1% of the work zone crashes are fatal, 38% result in injuries and 61% in property damage only crashes. Table 2.2 summarizes the studies' results concerning crash severity.

Table 2.2: Summary of Study Results Concerning Crash Severity

SUBJECT	STUDIES	RESULTS
Crash Severity	Ha and Nemeth *(33)* Nemeth and Migletz *(54)* Hargroves *(36)* Nemeth and Rathi *(55)* Rouphail et al. *(67)*	Work zone crashes are slightly less severe than non-work zone crash.
	Pigman and Agent *(62)* Summary Report on Work Zone Accidents *(69)*	Work zone crashes are more severe than non-work zone crash.
	Hall and Lorenz *(34)* Garber and Woo *(26)*	No difference between work zone and non-work-zone crash severity.

2.1.3. Crash Types at Work Zones

Several studies *(26, 29, 33, 34, 36, 54, 55, 62, 67, 69 and 77)* indicated that rear-end collisions are the predominant type of collision at work zones. Lervag and Fjerdingen *(44)* indicated that in addition to rear-end collisions at work zones, sideswipe and same directions crashes are over-represented compared to road sections without work zones. Khattak and Council *(42)* also found that rear-end collisions and sideswipe accidents are overrepresented in work zone areas compared to non-work zone areas.

2.1.4. Contributing Factors

2.1.4.1. Vehicles and Drivers Characteristics of Work Zone Crashes

Several studies *(26, 34, 62 and 67)* indicated that multi-vehicle crashes are over-represented at work zone areas. Moreover, some studies *(34, 55 and 62)* showed that heavy vehicles were overrepresented in work zone areas. Furthermore, Pigman and Agent *(62)* stated that work zone crashes involving heavy vehicles were more severe than work zone accident not involving heavy vehicles. Benekohal et al. *(4)* found that 90 % of truck drivers in a survey conducted in Illinois felt that driving through work zones was more hazardous than driving in other areas. Chambless et al *(10)* presented several drivers' behavior parameters that contribute work zone crashes:

- Misjudging stopping distance
- Following too closely
- Improper lane change

Garber and Zhao *(27 and 28)* suggested that a major causal factor for work zone crashes is speed related. The accidents are mainly caused by speed differentials resulting in a speed variance. Raub et al. *(66)* indicated that distraction from work in progress, failure to yield at the taper point, and excessive speed are over-represented causes for work zone crashes.

2.1.4.2. Environmental Characteristics at Work Zone Crashes

Pigman and Agent *(62)* found that night time (or during dark conditions) crashes are more severe than day time crashes. However, Nemeth and Migletz *(54)* indicated that day light or day time crashes at work zones are more severe than night time work zone crashes. Chambless et al. *(10)* indicated that road defects and vision obstruction are overrepresented parameters in work zone crashes. Raub et al. *(66)* indicated that narrower lanes and concrete barriers make it hard for drivers to maneuver and avoid accidents. Several studies were carried out to study the crash location distribution within work zones. Raub et al. *(66)* studied the location of crashes within work zones in Illinois. They divided work zones into four areas; the approach area, the taper area (transition area), the construction area, and the exit area. They found that:

- Almost 40% of the work zone accident occurred in the approach and transition area, and that more than 30% of this crashes involved injury and two vehicles.
- Crashes in the working area usually involved more than two vehicles, most commonly resulting in property damage only.

Garber and Zhao *(28)* also studied the location of crashes within work zones in Virginia by splitting the work zone into five areas; advance warning area, transition area, longitudinal buffer area, activity area and buffer area. Their results indicate that the activity area was the predominant location for crashes both in total number of accidents and in number of fatal accidents.

2.1.5. Traditional Safety Countermeasures at Work Zones

- **Warning lights:** Ullman et al., *(73)* stated that more colorful warning lights imply greater sense of urgency and they recommended the use of more colors, especially blue, for special flashing warning signs. A study conducted by Finley et al., *(19 and 20)* suggested that sequential warning light systems improve traffic safety by encouraging drivers to exit the closure lane farther upstream.

- **Fluorescent signs:** Fluorescent sheeting is different from ordinary sheeting because it absorbs short wavelength solar energy and then reemits the energy as longer wavelength visible lights. This increases the luminance of the sign. The increased luminance in turn provides greater contrast to the surroundings and hence, a more conspicuous signs *(44)*. Carlson et al. *(9)*, Fontaine et al. *(24)*, and

Eccles and Hummer *(16)* studied the benefits of fluorescent signs in work zones and concluded that the latter give some modest benefits.

- **Speed limit:** Speed differential at work zones is one of the most significant contributing factors to crashes. Several studies were undertaken to assess speed related enhancement methods that would reduce traffic speed in work areas. Maze et al. *(48 and 49)* indicated that work zone speed limit should be combined with other regulatory signs. Hall and Wrage *(35)* evaluated methods for enhancing motorist compliance with regulatory and advisory speeds in highway work zones and suggested that they might be improved by increasing the device's size and conspicuity. Several studies suggested the use of passive radars which are electronic radars that transmit in the microwave frequency band. Most studies *(9, 23, 24, 35 and 48)* concluded that passive radars have limited, if any, impacts on drivers' behavior in work zones. Several studies examined the effect of speed monitoring displays on reducing speeds at work zones. Studies by Hall and Wrage *(35)*, Fontaine and Hawkins *(23)*, Pesti and McCoy *(61)* and Maze et al. *(48)* confirm that these speed monitoring displays reduce the average speeds and improve speed compliance. Several studies tested the effect of using speed cameras on speed reductions at work zones. Elvik et al. *(17)* and Bolling and Nilsson *(6)* stated that the use of speed cameras can reduce speeds significantly at work zone.

- **Dynamic message signs:** Dynamic Message Signs (DMS) also termed Changeable Message Signs (CMS) or Variable Message Signs (VMS) are commonly used in work zones. Fontaine et al. *(24)*, Fontaine and Hawkins *(23)*, Garber and Srinivasan *(25)*, Andrew and Bryden *(2)* and Dudek et al. *(14)* conducted studies to explore the effectiveness of DMSs. Their results are consistent in terms of the positive effectiveness of the signs both in giving guidance and information during lane closure and somewhat in reducing speeds. Walton et al. *(75)* evaluated the Kentucky's DMS in an effort to draw recommendations for better effectiveness of these DMSs. Authors found that DMSs should not be used to:

    - Replacement of static signs, regulatory signs, pavement markings, standard traffic control devices, conventional warning or guide signs.
    - Replacement of lighted arrow board
    - Advertising
    - Generic messages (e.g. welcome to our state)
    - Test messages
    - Weather related activities
    - Describing recurrent congestions
    - Time and temperature
    - Public service announcement (general traffic safety and non-traffic-related announcements)

- **Pavement markings and rumble strips:** The term pavement markings comprise means of communicating roadway information to drivers. According to several studies *(22, 23, 24 and 57)* rumble strips can reduce work- zone accident rates significantly. Berndhardt et al. *(5)* showed the importance of pavement markings at work zones especially in guiding the drivers through the work area.

- **Arrow panels**: Arrow panels are commonly used in with work zones guiding the drivers to merge to the open lane *(57)*. The Oregon department of transportation studied the effectiveness of a "sequentially flashing diamond" arrow panel display as an advance warning caution warning in temporary work zones and the results show that the diamond display mitigated speeds significantly *(30)*.

2.1.6. Factors Affecting Work Zone Capacity

Maze et. al. *(47)* published a report titled "Synthesis and Procedures to Forecast and Monitor Work Zone Safety and Mobility Impacts" where they summarized the variables known to affect work zone operations (i.e. capacity). Table 2.3 below is borrowed from the report and exposes these variables. In addition to creating safety issues, work-zones are responsible for almost 24% of the non recurring congestions on the United States highway system and are ranked second to cause drivers dissatisfaction *(40)*. Therefore, several states, in an effort to enhance safety and mobility at work-zones, deployed ITS technologies in work areas commonly referred as Smart Work Zones (SWZs). The SWZ usually provides advanced traveler information to drivers to advise of delay and assist them in deciding whether to use alternate routes. Other types of SWZ were designed to address concerns with speed management and lane merging conflicts in work-zones. Several factors are associated with the success of these systems such as age, gender, trip purpose, network familiarity, education, and trust in the messages content. According to Peeta et al. *(60)* the responsiveness of the drivers to these messages increased when at least two pieces of information are provided together.

Table 2.3: Variables known to impact work zone capacity (Source: Maze et. al. *(47)*)

Variable impacting capacity	Attributes associated with variable	Known characteristics
Work zone lane closure configuration	The capacity of a lane closure is dependent on the number of lanes left open and closed and the location of the lane or lanes closed.	When one or more lanes are closed, the remaining open lane(s) have less capacity than normal through lanes. For example, when one lane of a two-lane segment is closed, the open lane has less capacity than one normal lane due to merging. Also, right lane closures result in lower capacity than left lane closures because the right lane generally carries more traffic, resulting in more vehicles merging into the open lane.
Intensity and location of work	The capacity of the open lane will be impacted by visible construction work in proximity to the open lane(s).	Even when there is a concrete barrier between the driver and the construction activity, drivers will slow when the work is in close proximity to the open lane. Intensity and location of work have been found to negatively impact capacity by 1.85%–12.5%.
Percentage of heavy vehicles	Due to their poor speed change performance, high percentages of heavy vehicles will reduce capacity of the through lanes.	Because of poor speed change performance, trucks have a greater impact on capacity after queuing than during free flow. On level terrain and in work zone merge areas, trucks equal 2.4 passenger cars and buses equal 1.5 passenger cars.
Driver characteristics	Drivers that have experience with the work zone are likely to select shorter headway, and capacity will increase.	Commuters making routine trips are familiar with the work zone and are more likely to reduce headways through the work zone. During off-peak hours, capacity reduces by approximately 7% and, during the weekends, by 16%.
Entrance ramp locations and volumes	Ramps in the area of the work zone are likely to create more turbulence in the traffic flow and reduce capacity.	The capacity of the open lanes should be reduced by at least the volume of the ramp within or downstream of the taper.
Grade of lane closure	Positive grades will diminish the capacity of open lanes, particularly where there is a high proportion of heavy vehicles.	At only a 3% grade, passenger car equivalent factors for trucks increased from 2.4 to the range of 2.7–3.2. Positive grades are likely to have the greatest impact if they are located at the lane closure merger point.
Duration of work	As the work zone duration increases, drivers are more likely to be familiar with the work zone and reduce their headways, thus increasing the capacity of the work zone with time.	See comments above for driver characteristics.
Weather conditions	The *Highway Capacity Manual 2000* contains reductions in maximum volumes due to weather.	During trace rainfalls, urban freeway capacity is reduced by 1%–3%; in rainfalls of 0.01–0.25 inches per hour, capacity is reduced by 5%–10%; and for rainfalls above 0.25 inches per hour, capacity is reduced by 10%–17%.
Work time	When work is scheduled at night to avoid peak travel times, traffic control presents significant challenges. Drivers are more frequently impaired by drugs or fatigue and generally behave differently due to lower visibility and glare caused by roadway lighting.	Significant differences in traffic flow exist for nighttime work zones and for daytime work zones.
Location of merge point and enforcement	Merging upstream from the taper point of a lane closure increases capacity more than late merging. However, when using early merge, drivers not following expected merge discipline skip to the head of the queue and force themselves into it, creating a crash risk and turbulence, thus diminishing any efficiency gained through an early merge.	Very little is known about the benefits of enforcement, and most studies of enforcement focus on safety benefits, as opposed to traffic flow efficiency benefits. It is believed that using enforcement personnel to support smooth behavior improves traffic flow.

2.2. ITS Applications in Work Zones

2.2.1. Minnesota Smart Work Zone

In 1996, the Minnesota Department of Transportation was one the first state departments of transportation to deploy and begin experimenting the smart work-zone concept. Their system used several semi-portable field units that transmit traffic data to the Traffic Management Center (TMC). The data is reviewed by an operator at the TMC and messages were displayed on the permanent and portable message signs in the vicinity of the work-zone accordingly *(68)*.

2.2.2. Wisconsin Smart Work Zone

A field study was conducted in Wisconsin to investigate the drivers' response to the messages displayed by the SWZ signs in a rural area. The messages displayed by the signs included the distance to the work zone taper and the travel time to the end of the work zone. Alternate route advisories were not provided to drivers on the dynamic message signs. However, alternate routes were marked on static signs should motorists choose to use alternate routes. The results by Horowitz *(38)* indicated that alternate route selection increased by 7 to 10 per cent during peak hours.

2.2.3. Nebraska Smart Work Zone

A field study was conducted in Nebraska to explore the response of drivers to advanced advisory information approaching a work-zone. In this application of the SWZ concept, when delay exceeded 5 minutes' delays advisories were provided. When delays exceed 30 minutes a message "CONSIDER ALT ROUTE" is displayed without specific alternate route advisory. Alternate route use increased from 7% when the signs were blank to 11% of freeway traffic when an alternate route advisory was provided *(22)*.

2.2.4 Arkansas Smart Work Zone

A SWZ system, similar to the Nebraska and Wisconsin system, was deployed in Arkansas. Tudor et al. *(72)* conducted a study where they compared the crash rates of the SWZ to two other control sites with similar characteristics with no SWZ. Using the number of crashes per million vehicle miles traveled as a measure of effectiveness, the fatality rate decreased from 3.2 and 3.4 at the sites without the SWZ system to 2.2 at the sites with the SWZ system. The average overall crash rate reduction was 33%. The average rear-end crash reduction was 7%. Traffic counts also showed that the alternate route use increased when back-up advisory message without identifying alternate route was displayed.

2.2.5. Missouri Smart Work Zone

Another SWZ system was deployed and explored in Missouri. King et al. *(43)* examined the use of this system that consisted of an automated system which advises drivers when delays and speed reductions were occurring at work zone sites. The analysis showed that this system had a positive effect on the safety of work zone. In fact, there was a positive effect on the reduction of the mean speed and the speed variance as the traffic neared the work zone.

2.2.6. Michigan Smart Work Zone

A different type of SWZ system was deployed in Michigan. A variable speed limit (VSL) system was deployed in Michigan to manage speeds through work-zones under different traffic and environmental conditions. The system monitors traffic flow and the surface condition to detect the presence of water, ice, or snow. Based on these conditions speed limits are determined and posted for drivers. As a conclusion, Lyles et al. *(45)* stated that the VSL system can present far more credible information (realistic speed limits) to the motorist, responding to both day-to-day changes in congestion as well as significant changes in congestion and geometry as motorists go through a given zone.

2.2.7. North Carolina Smart Work Zone

The North Carolina Department of Transportation (NCDOT) was concerned about the safety and mobility of drivers on I-95 since it was undergoing major rehabilitation and resurfacing. To address their concerns the NCDOT begun deploying advanced technology to enhance safety and mobility of their work-zones. A system that consisted of portable changeable message signs located along the approach of the work zone site providing motorists with advisory information of delays and suggesting alternate routes when necessary. The results showed that alternate route use increased from 10 to 15 per cent. Moreover, a survey conducted showed that 80% of the drivers were pleased with the information given by the dynamic signs. As for the safety improvements the authors indicated that there were not enough data to draw conclusions concerning the safety of drivers in work-zones with the deployment of the SWZ system *(7)*.

2.3. Previous DLM Applications

When traffic demand exceeds the capacity of a work-zone, queues expand beyond the advance warning signs, often surprising the oncoming vehicles thus increasing the crash potential. The early and late merge routines are two strategies that were designed with the intent to resolve these problems. The early merge and late merge strategies take two forms: static and dynamic. The following sections elaborate on these systems.

2.3.1 Early Merge Strategy

The early merge strategy encourages earlier merging in advance of work-zone lane closures to lower the potential for merging friction at the merge point of a lane closure. A disadvantage of this strategy is that it requires additional signage and supplementary control measures further upstream of a lane closures which can make the maintenance of traffic control more difficult *(3)*. The early lane merge strategy can take two forms: static and dynamic. These two concepts will be further explained.

2.3.1.1. Static Form

The static form of lane merging does not change in real time in response to traffic conditions. The static form typically includes additional “LANES CLOSED” sings placed upstream of lane closure on average at 1-mile intervals *(50)*. The static early merge strategy is intended to mitigate rear-end collisions by forewarning drivers of latent slowing traffic. Other static methods for promoting early merging comprise the use of supplementary control measures *(3)*. Bernhardt et al. *(5)* studied numerous supplementary traffic control measures to encourage early merging at work-zones. Bernhardt et al. *(5)* evaluated several supplementary traffic control measures including the following:

- White lane drop Arrows: This method led to a 4.2% increase in the number of vehicles in the open lane at the work-zone taper. Mean speeds decreased by 6.1 mph under congested conditions. The number of vehicles below the speed limit under uncongested conditions increased by 14.8%. A decrease of 10.3 mph in the mean speeds of the fastest 15 % of vehicles occurred under congested conditions.
- The Wizard Work Zone Alert and Information by TAFCON: This method led to an increase in the number of vehicles in the open lane by 12.4% under congested conditions. The number of vehicles traveling below speed limit increased by 11.7% under uncongested conditions.
- Orange rumble strips as a supplement to the standard lane merge configuration: This method increased the number of vehicles in the open lane at the start of the work- zone taper during congested conditions by 10.2%. For uncongested conditions, the means speeds in the closed lane decreased by 16.1 mph. Uncongested 85th percentile speeds decreased by 6.9 mph and the mean speed of the fastest 15% of vehicles decreased between 6.7 mph and 15.1 mph.

According to Datta et al. *(11)*, the static lane merge system may confuse drivers, especially under uncongested conditions where the travel speed is high, and the volume is low. Nemeth and Rouphail *(56)* found through a simulation study that the early merge strategy significantly reduced the frequency of forced merges, especially at higher traffic volumes. Another simulation study by Mousa et al. *(53)* determined that the early merge strategy increased the travel times through the work-zone because the vehicles are more likely to be delayed over greater distances by slower vehicles ahead of them in the open lane.

2.3.1.2. Dynamic Form

The dynamic early merge system creates a NO-PASSING zone upstream of a work-zone taper based on real-time measurements of traffic conditions *(70)*. The system consists of queue detectors and “DO NOT PASS WHEN FLASHING” signs that would be triggered by the queue detectors. When a queue is detected next to a sign, the next closest sign’s flashing strobes, upstream, are activated creating the NO-PASSING zone. This system makes queues jumping an illegal task. Figures 2.1 and 2.2 illustrate this system**.**

The Indiana Lane Merge System (ILMS) was tested in the field in the 1997 construction season by the Indiana Department of Transportation. It was found that the system smoothes the merging operations in advance of the lane closures. Drivers merged when they were supposed to merge, the flow in the open lane was uniform, and rear-end accident rates decreased. However, this system did not increase the throughput and the results of a simulation study conducted by Purdue University indicated that travel times through work-zones with ILMS are larger *(71)*.

In 1999, the University of Nebraska conducted a study of the ILMS on I-65 in the vicinity of Remington, Indiana. This study was limited to a four day data collection exclusively under uncongested conditions. In this project, the right lane was closed and the data collected (by video cameras and laser speed gun) and extracted included traffic volumes, speeds, conflicts, lane distributions, flows, and time headways. Comparing the ILMS with the standard Manual on Urban Traffic Control Devices (MUTCD) merge control, the results showed that the ILMS increased the capacity to some extent (from 1,460 to 1,540 vphpl). As for the safety aspect of the ILMS, since the data collected was limited to uncongested conditions and to 16 hours of video data, it was not clear whether the ILMS improve safety in terms of number of forced merges *(51)*.

The ILMS was also studied by Purdue University and the results were detailed in a report published in 2001. This system was studied on I-65 near West Lafayette, Indiana. This project entailed extensive data collection under both congestion and uncongested conditions for a duration of four months in 1999. Multiple loop detectors and two cameras were used for data collection. Purdue University studied both the safety effects of the ILMS by developing conflict frequency models as well as capacity effects of the ILMS. The results of the analyses showed that the ILMS decreases the capacity by 5%. The authors mentioned that the decline in the capacity may be due to the unfamiliarity of the drivers with the system *(70)*.

The Wayne State University *(76)* conducted a study to assess the ILMS commonly referred to as Michigan Lane Merge Traffic Control System (LMTCS). This study compared four sites where the system was installed to four control sites where traditional MUTCD merge was implemented. The “DO NOT PASS WHEN FLASHING” signs were activated manually by personnel on the four sites. The lane closure configuration and geometry of freeway sections were homogeneous in the test and control sites for consistency. The data collected included aggressive driver behavior, location of merging, presence of law enforcement. In addition to that, the floating car method was utilized to record travel times and delays. According to their results the ILMS (or LMTCS) increased the average operating speed, decreased the delays (49 vehicle hours of delay per hour), and decreased the number of aggressive driving maneuvers during peak hours (from 73 to 33).

The results of the studies on dynamic early merging are mixed. The Wayne State study showed an increase in average operating speeds, a decrease in average delay, no difference in capacity, and a decrease in the number of aggressive driving maneuver during the peak hour *(76)*. The Nebraska study showed few forced merges with the ILMS, however, it was unclear whether this was a result of the ILMS or it was due to the lack of congested conditions during the study. The Nebraska study estimated that the ILMS increases the capacity from 1,460 to 1,540 vphpl *(51)*. The Purdue University study showed that the dynamic early merging decreased capacity by 5% *(70)*. Table 2.4 summarizes the advantages and disadvantages of the dynamic early merge strategy.

Table 2.4: Summary of Early Merge Strategy

Static Early Merge		**Dynamic Early Merge**	
Advantages	**Disadvantages**	**Advantages**	**Disadvantages**
Reduces the frequency of forced merges especially at higher traffic volume (*Nemeth and Rouphail, (56)*).	Requires additional signage and supplementary control measures which makes maintenance more difficult (*Beacher et al.,(3)*)	Smoothes the merging operations in advance of a lane closure (*Tarko et.al., (71)*)	Travel times through work-zones are larger (*Tarko et.al., (71)*)
	May confuse drivers under uncongested condition (*Datta et al., (11)*)	Rear-end Accident rates decreased (*Tarko et.al.,(71)*)	Decrease capacity by 5% (*Tarko and Venugopal, (70))*
	Increase travel time through the work-zone (*Mousa et al. (53)*)	Increase the capacity of work-zones under UNCONGESTED conditions *(McCoy et al., (51))*	Unfamiliarity of confusion of the drivers with the systems (*Tarko and Venugopal, (70)*)
		Decrease delays (*Wayne State University, (76*)	
		Decrease in number of forced merges (*Wayne State University, (76)*)	

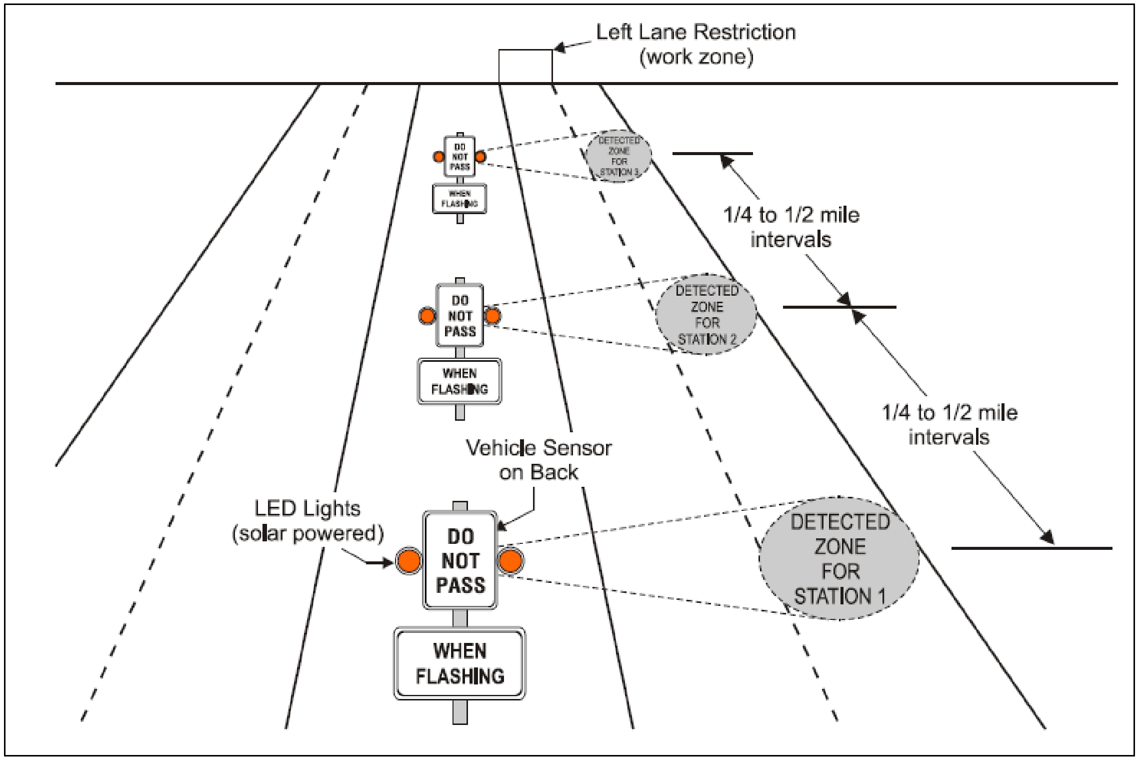

Figure 2.1: Indiana Lane Merge System (Source: Beacher et al., *(3)*)

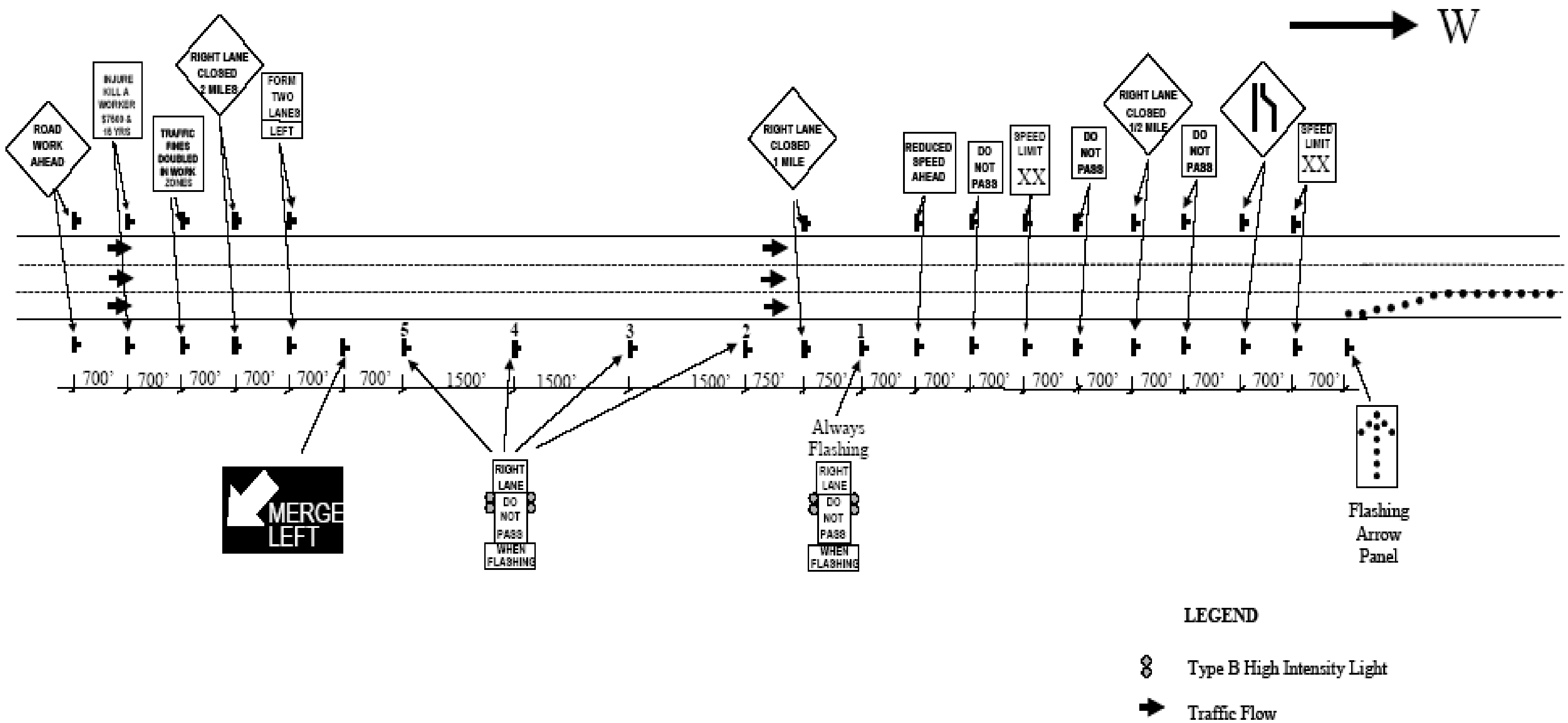

Figure 2.2: Dynamic Early Lane Merge Traffic Control System Used in Michigan (Source: Datta et al., *(11)*)

2.3.2. Late Merge Strategy

The concept behind late merge is to make more efficient use of roadway storage space by allowing drivers to use all available traffic lanes to the merge point. Once the merge point is reached, the drivers in each lane take turns proceeding through the work-zone. The combined effect of maximized storage and orderly merging operations may have the potential to increase throughput, reduce queue lengths, shorten travel times, and discourage aggressive driving *(3)*.

2.3.2.1. Static Form

The Pennsylvania Department of Transportation (PennDOT) introduced the static form of the late merge to mitigate aggressive driving and road rage at merge points *(3)*. The PennDOT's late merge strategy's traffic control plan comprises signs calling for "USE BOTH LANES TO MERGE POINT" 1.5 miles upstream of the work zone and "MERGE HERE TAKE YOUR TURN" near the beginning of the taper (See Figure 2.3). The static late merge strategy was examined by a study conducted in Nebraska and another study conducted by the Texas Transportation Institute (TTI). The Nebraska's research was limited to a 2-to-1 lane reduction scenario. Comparing this static late merge strategy to the standard MUTCD lane merge strategy, the results showed 75% fewer forced merges and an increase from 1,460 to 1,730 pcph in capacity. This study also suggested that an effective signing plan be made available to optimize the potential of the concept. This study also showed that trucks had more difficulty merging from left to right than right to left *(51)*.

The TTI explored the late merge concept in a 3-to-2 lane closure scenario. The data collection was limited to 1 day under standard MUTCD lane closure and to 1 day under the static late merge strategy. The results of the comparison showed that the late merge strategy delayed the onset of the congestion by 14 minutes, reduced queue length from 7,800 to 6,000 feet. Moreover, an analysis of volumes by lane showed that a larger percentage of vehicles used the open lane with the late merge in place and that more vehicles were able to pass through the merge point *(74)*. On the other hand, the University of Nebraska conducted a survey in Pennsylvania to explore the opinion of the drivers regarding the late merge system application. Sixty percent of the truck drivers versus 22 percent of the passenger car drivers stated that they experienced or observed other drivers having difficulty merging. This could be related to the fact that 73% of the truck drivers and 40% of the passenger car drivers did not believe that the signs worked *(8)*.

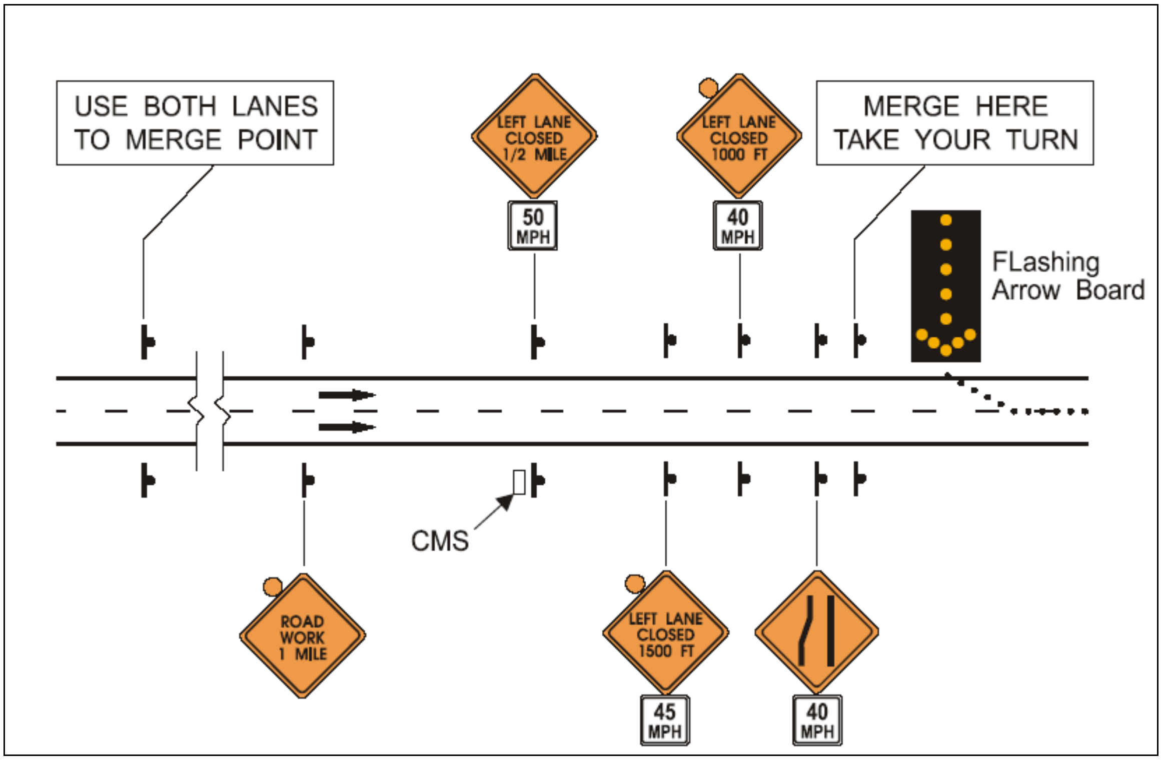

Figure 2.3: PennDOT's Late Merge Concept (Source: Beacher et al., *(3)*)

2.3.2.2. Dynamic Form

McCoy and Pesti *(50)* expressed their concern about the confusion of drivers at the merge point with the late emerge in place. To solve this issue, they proposed a dynamic late merge in which the late merge would be employed only at times of high congestion. They stated that the late merge can reduce congestions and delays, whereas the early merge increased congestions and delays. Beacher et al. *(3)* applied the dynamic late merge system in Tappahannock, Virginia and conducted a before and after study to explore the benefits of the system. Figure 2.4 shows the site diagram with the dynamic late merge system. According to their results, the percentage of vehicles in the closed lane increased significantly from 33.7 to 38.8 percent when comparing the late merge to the MUTCD treatment. The throughput volumes showed no statistical difference between the MUTCD treatment and the late merge. Time in queue was not significantly different between the two types of traffic control.

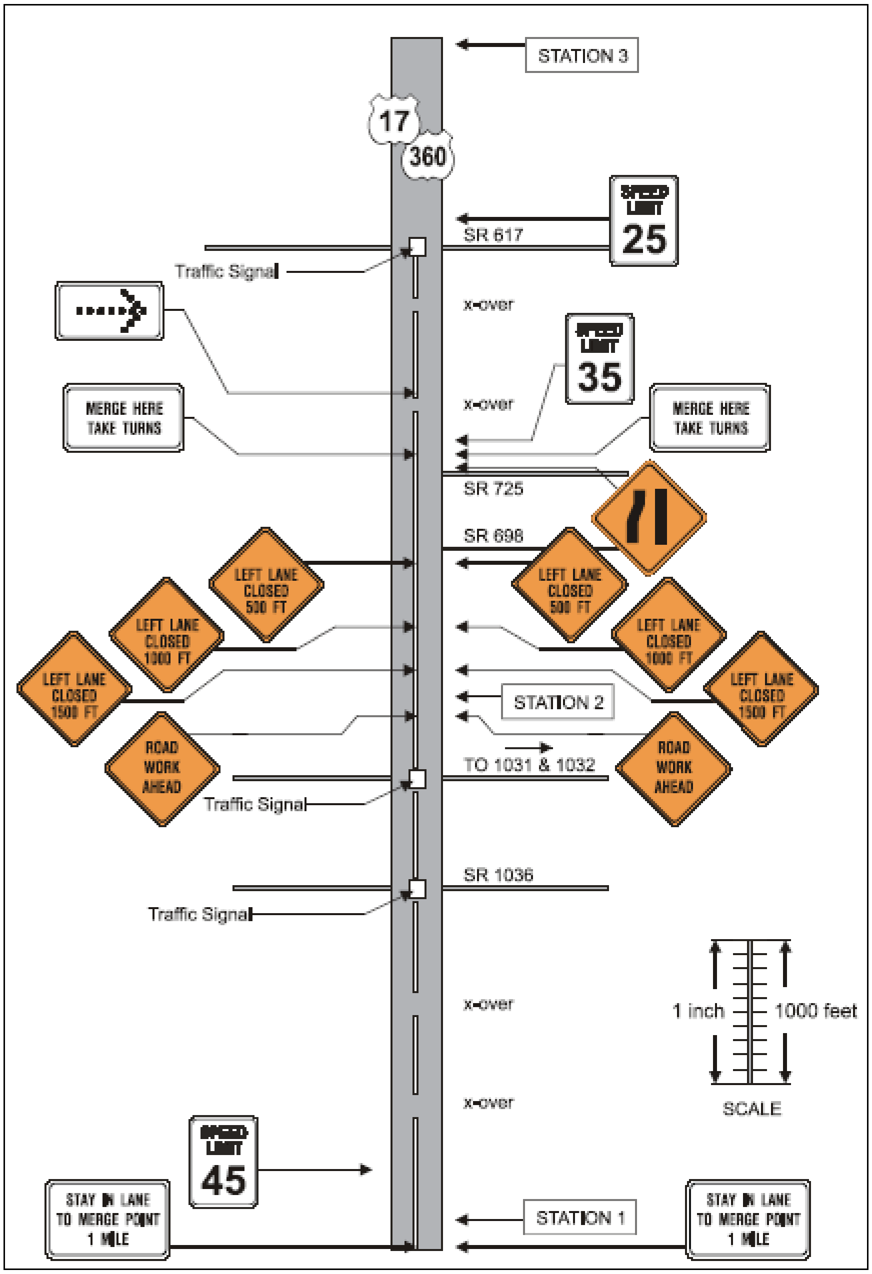

Figure 2.4: Tappahannock, Virginia site diagram (Source: Beacher et al., *(3)*)

According to Beacher et al. *(3)* the lack of improvement in throughput and time in queue may be attributable to the relatively low percentage of heavy vehicles. They proposed some guidelines for the application of the dynamic late merge system:

- Two-to-1 lane closure: the late merge should be considered for 2-to-1 lane closure configurations to improve throughput when large numbers of heavy vehicles are present (>20%) for the majority of the time and congestion and queuing are often present.

- Three-to-1 lane closure: while the simulation results showed that the late merge significantly improved throughput for all situations, there are no documented evaluations of the deployment of the lat merge in this configuration. Further research is needed to determine how the late merge could be deployed in this type of configuration to ensure driver understanding of the signs.
- Three-to-2 lane closure: The late merge should be considered in the 3-to-2 configuration as a possible means to improve flow when heavy vehicles represent more than 20 percent of the traffic stream and congestion and queuing are frequent.

In June 2003, the University of Kansas, in cooperation with the Kansas Department of Transportation and the Scientex Corporation deployed the Construction Area Late Merge (CALM) system in Kansas *(52)*. This system is the dynamic version of the Late Merge Concept introduced by PennDOT (See Figure 2.5). This system employs traffic detectors to sense congestion upstream of a construction lane closure. The traffic data is communicated in real-time to a central controller where proprietary software algorithms determine the critical thresholds of traffic density and speed to activate real-time messages directing motorists to remain in their lanes until they approach the lane closure, where they merge alternately by taking turns. The CALM system provides real-time safety alerts to motorists. This system is configured to operate as an early merge system under light traffic loads and as a late merge system under heavier traffic loads. Meyer *(52)* reported that the compliance of the drivers with the system increased with time and recommended that drivers be familiarized and trained to the system to optimize the potential merit of the system. The average volume through the work-zone was enhanced after the drivers were accustomed with the system. However, the net change in volume did not show a significant improvement over baseline values. Like others, this system also utilized wireless communication between RTMS detectors and portable CMS to display lane use instructions to drivers based on traffic conditions. This system was designed to operate in three distinct modes- Early merge, late merge, and incident. The incident category was a special case of the late merge strategy when traffic speeds were exceptionally low. Transitions between the modes occurred seamlessly based on the current traffic average operating speeds and transition thresholds between the three modes. According to the results, the late merge systems have the potential to improve freeway operations around construction lane closures. The evaluations also highlighted the importance considering the location of entrance and exit ramps when placing the signs and sensors.

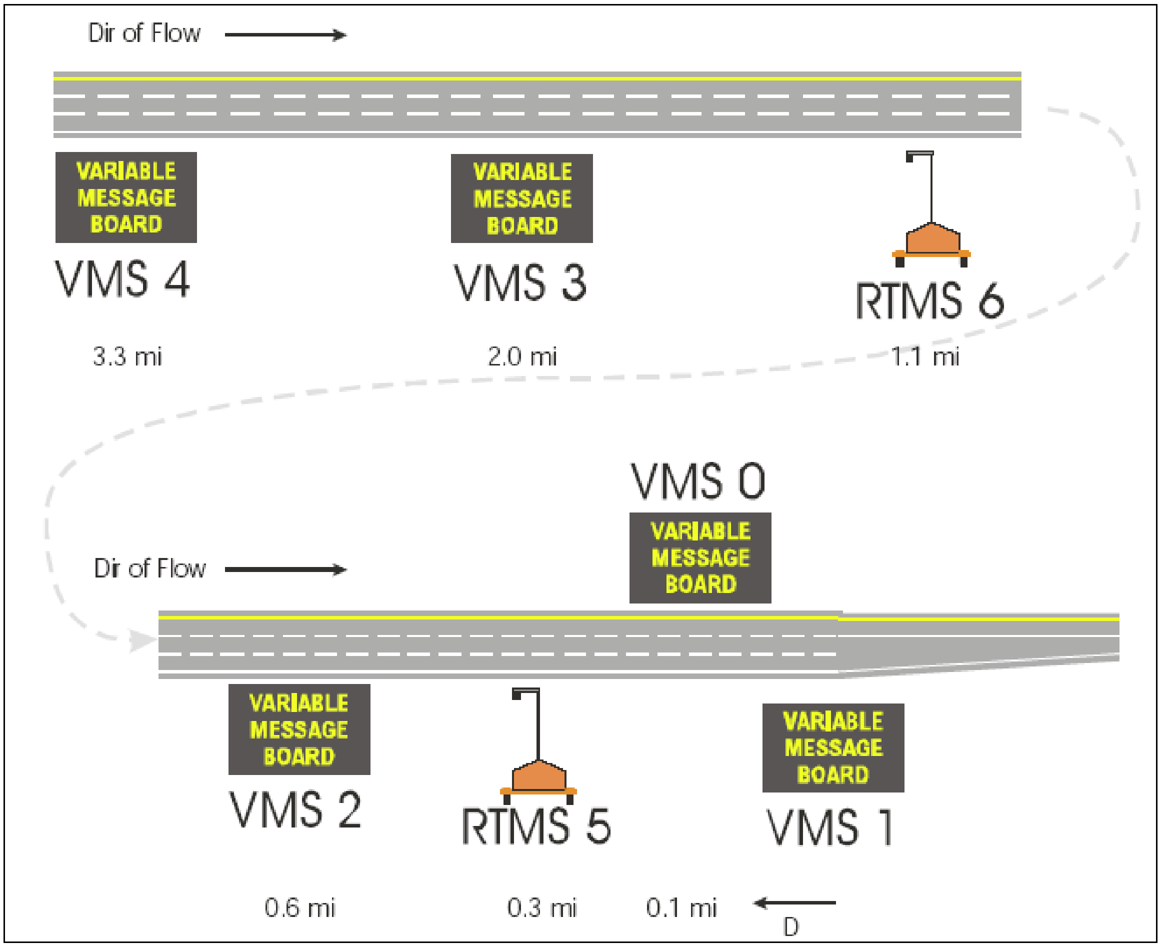

Figure 2.5: CALM System Field Components (Source: Meyer, *(52)*)

Maryland's DLM System *(1)* comprises a set of four portable CMS and three RTMS detectors that are added to the standard static traffic control devices utilized at construction lane closures. The CMS furthest upstream (~1.5 miles) from the taper alternated between the messages "USE BOTH LANES" and "TRAFFIC BACKUP". The next two CMS located at approximately ½ mile and ¼ mile from the taper itself, the final CMS alternated between messages "TAKE YOUR TURN" and "MERGE HERE". The location of the CMS and RTMS are shown in Figure 2.6. The University of Maryland, College Park conducted the evaluation of the system by utilizing one day of baseline (or control) data where the road closure utilized only the standard static traffic control signs. This was followed by four days with the DLM system activated. Four measures of effectiveness were evaluated; work-zone throughput, lane volume distribution, maximum queue length, and simulation data analysis. According to the findings, the DLM increased the work-zone throughputs when compared to the baseline conditions. Traffic volumes collected during 10-minute intervals during the four days of DLM system deployment were higher than under the baseline conditions. Another method of investigating traffic throughput utilized a calibrated computer simulation. Lane volume distribution was also compared under the baseline and DLM System conditions. The results showed that more vehicles were in the discontinuous lane. Many drivers were observed merging before the designated merge location during the evaluation period. These early merges resulted in multiple merging points and appeared to result in some confusion on the proper place to merge. The queue lengths were observed to be reduced between 8% and 33% during the four days evaluation with the activation of the DLM System. Unfortunately, numerous traffic conflicts were observed between the two-lane traffic. Many vehicles were observed making forced merges at the taper point because they were not allowed to merge.

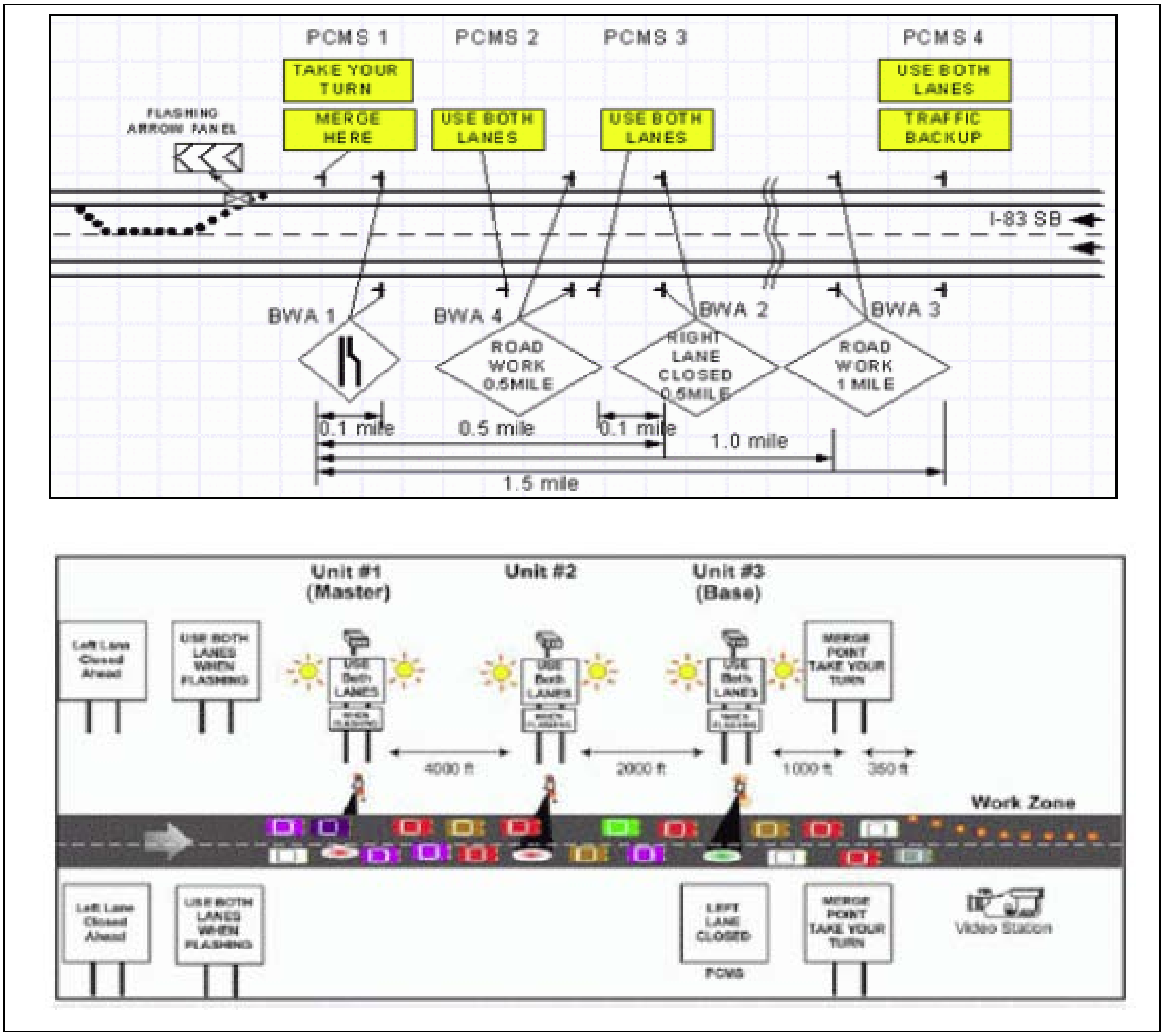

Figure 2.6: Maryland's DLM - An Applied Technology and Traffic Analysis Program

These conflicts resulted in conditions of stop and go traffic. The authors finally stated that the advantages of the DLM system are increased throughput, shorter queue lengths, and more uniform distribution of lane use before the taper. The disadvantages were listed as increased stop and go conditions and multiple merging points. The authors recommended that future deployments could comprise variable speed limit signs, change the distance between the DLM system equipment based on perception/reaction time and on site-speed characteristics and remove separate static merging signs for the DLM system to avoid confusion on the correct merging location.

The Minnesota Department of Transportation (MnDOT) evaluated the Dynamic Late Merge System which consists, in addition to the standard orange and black warning signs placed in advance of the lane closure, of three CMS and a RTMS detector *(15)*. When congestion begins to form, the signs are activated to provide lane use instructions to drivers. The CMS farthest from the work-zone displays the message "STOPPED TRAFFIC AHEAD-USE BOTH LANES". The next CMS sign reads "USE BOTH LANES-MERGES AHEAD". The sign closest to the work zone will show alternating messages of "TAKE TURNS-MERGE HERE" (Figure 2.7). When traffic speeds increase as congestion dissipates, the signs will turn off and the system will return to the typical static work zone traffic control that encourages early merging.

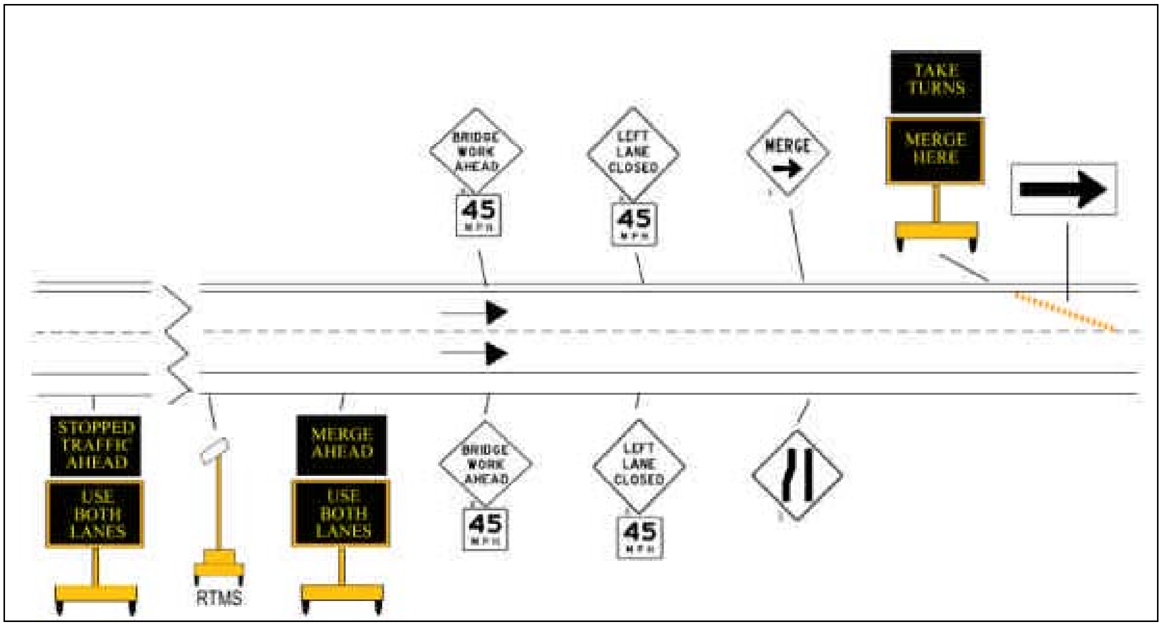

Figure 2.7: Minnesota's Dynamic Late Merge System Evaluation

The results of the Minnesota 2004 study showed:

1. The use of the discontinuous lane increased dramatically when the CMS were activated. During the heaviest demand, the discontinuous lane use percentage increased to levels of almost 60% at locations approximately half-mile from the construction taper.
2. The queue lengths were observed to be relatively minimal. It was also observed that some drivers refused to use both lanes and wait in a long single queue.
3. The overall driving conditions were improved upstream of construction lane closures.

4. The maximum volume throughput within the single lane construction closure at deployment locations was nearly identical.

Grillo et al. *(31)* deployed the dynamic late merge system referred to as Dynamic Late Lane Merge System (DLLMS) on I-94 in the state of Michigan. Their results indicated that compared to the conventional work zone system, the DLLMS improved the flow of travel and that the monetary benefits of DLLMS outweigh the cost of the system. In Table 2.5, we summarized the advantages and the disadvantages of the Late Merge strategy. Moreover, Beacher et al. *(3)* presented a table (See Table 2.6) summarizing a comparison between the early and late merging strategies in terms of safety and operations.

Table 2.5: Summary of Late Merge Strategy

Static Late Merge		**Dynamic Late Merge**	
Advantages	**Disadvantages**	**Advantages**	**Disadvantages**
75% fewer forced merges (*McCoy et al., (51)*)	Confusion of drivers at the merge point when the static form is employed during low congestions (*McCoy and Pesti, (50)*)	Work-zone throughputs increased *(1)*	No difference in time in queue when truck percentage is lower than 20% (*Beacher et al., (3)*)
Increase in capacity from 1,460pcph to 1730pcph (*McCoy et al., (51)*)		Queue lengths were reduced between 8% and 33% *(1)*	No difference in the throughput volume when truck percentage is lower than 20% (*Beacher et al., (3)*)
Delayed the onset of congestion by 14 minutes (*Byrd, (8)*)		Reduced queue length *(15)*	Increased stop and go at the taper point *(1)*
Reduced queue length from 7,800ft to 6,000ft (*Byrd, (8)*)		Enhance the overall driving condition upstream of the lane closure *(15)*	

Table 2.6: Comparison Between Early and Late Merge (Source: Beacher et al.; *(3)*)

Factor	Standard MUTCD Closure	Late Merge		Early Merge	
		Static	Dynamic	Static	Dynamic
Capacity (pcph)	1,460[5] 1,320[17]	1,730[5]	1,820[16] (estimated)	No data available	Conflicting data: Decreased 5% in one study,[17] 1,540 capacity in another [5]
Forced Merges	20/hr[5]	Decreased 75%[5]	No data available	Decreased[4]	1/day[5]
Cost Impact		Increases $6/day	Increases $120/day[5]	No data available	Increases $120/day[5]
Lane Distribution		Volume increased 30% in closed lane [5]	No data available	Volume increased 12.4% in open lane[4, a]	Volume increased 20% in open lane[5]
Mean Speed (vs. standard MUTCD)		Decreased 7 mph (uncongested)[5] Decreased 32 mph (congested)	No data available	Decreased 16.1 mph (uncongested)[4, b]	Decreased 2 mph (uncongested) [5]
Queue Length		Decreased 50%[5] Decreased 23%[3]	No data available	No data available	No data available

[a] Superscript numbers refer to the reference for the pertinent study.
[b]Test results based on inclusion of white lane drop arrows and Wizard.
[c]Test results based on inclusion of orange rumble strips.

3 Walters, C.H. and. Cooner, S.A., "Understanding Road Rage: Evaluation of Promising Mitigation Measures" Report 4945-2, Texas Transportation Institute, College Station, 2001.
4 Bernhardt, K.L.S., Virkler, M.R. and Shaik, N.M., "Evaluation of Supplementary Traffic Control Measures for Freeway Work-zone Approaches", Paper presented at the 80th Annual Meeting of the Transportation Research Board, Washington D.C., 2001.
5 McCoy, P.T., Pesti, G. and Byrd, P.S., "Alternative Information to Alleviate Work Zone Related Delays", SPR-PL-1(35) P513, University of Nebraska, Lincoln, 1999.
16 McCoy, P.T., and Pesti, G., "Dynamic Late Merge Control Concept for Work Zones on Rural Interstate Highways", Paper Presented at the 80th Annual Meeting in Transportation Research Record, Washington D.C., 2001.
17 Tarko, A., and Venugopal, S., "Safety and Capacity Evaluation of the Indiana Lane Merge System" FHWA/IN/JTRP/-2000/19, Purdue University, West Lafayette, Ind., 2001.

3. SIMPLIFIED DYNAMIC LANE MERGING SYSTEM

3.1. Current Florida MOT Plans

Currently the Florida Department of Transportation deploys an MOT plan known as the MAS. According to the Florida Plans Preparation Manual *(21)*, the MAS aims at increasing the motorist awareness of the presence of active work and at providing emphasis on reduced speed limits in the active work area. The Florida manual states that the MAS shall be used on multilane facilities where the posted speed limit is 55mph or greater and where work activity requires a lane closure for more than five days only when workers are present. The MAS, as shown in Figure 3.1, consists of Portable Regulatory Signs (PRS) highlighting the regulatory speed for the work zone and a Radar Speed Display Unit (RSDU) displaying the motorist's work zone speed. The MAS also comprises a PCMS, a lane drop warning sign, a speeding fines doubled warning sign, in addition to road work ahead warning signs.

3.2. Modified MOT Plans

The modified MAS plans consist of the addition of an ITS-based lane management system to the conventional MAS. Two modified MAS plans (early SDLMS and late SDLMS) are suggested. The first modified MAS plan is a simplified dynamic early merge system and the second modified MAS plan is a simplified dynamic late merge system. Therefore the conventional MAS plans are supplemented with one PCMS and a non-intrusive RTMS trailer as shown in Figure 3.2. The modified MAS plan is referred to in this paper as SDLMS. The additional PCMS and sensor trailer are placed at the same location in both modified MAS plans. The messages displayed by the PCMS will differ as elaborated on in the next section. The modified MOT plans were signed and sealed by a Florida licensed consultant.

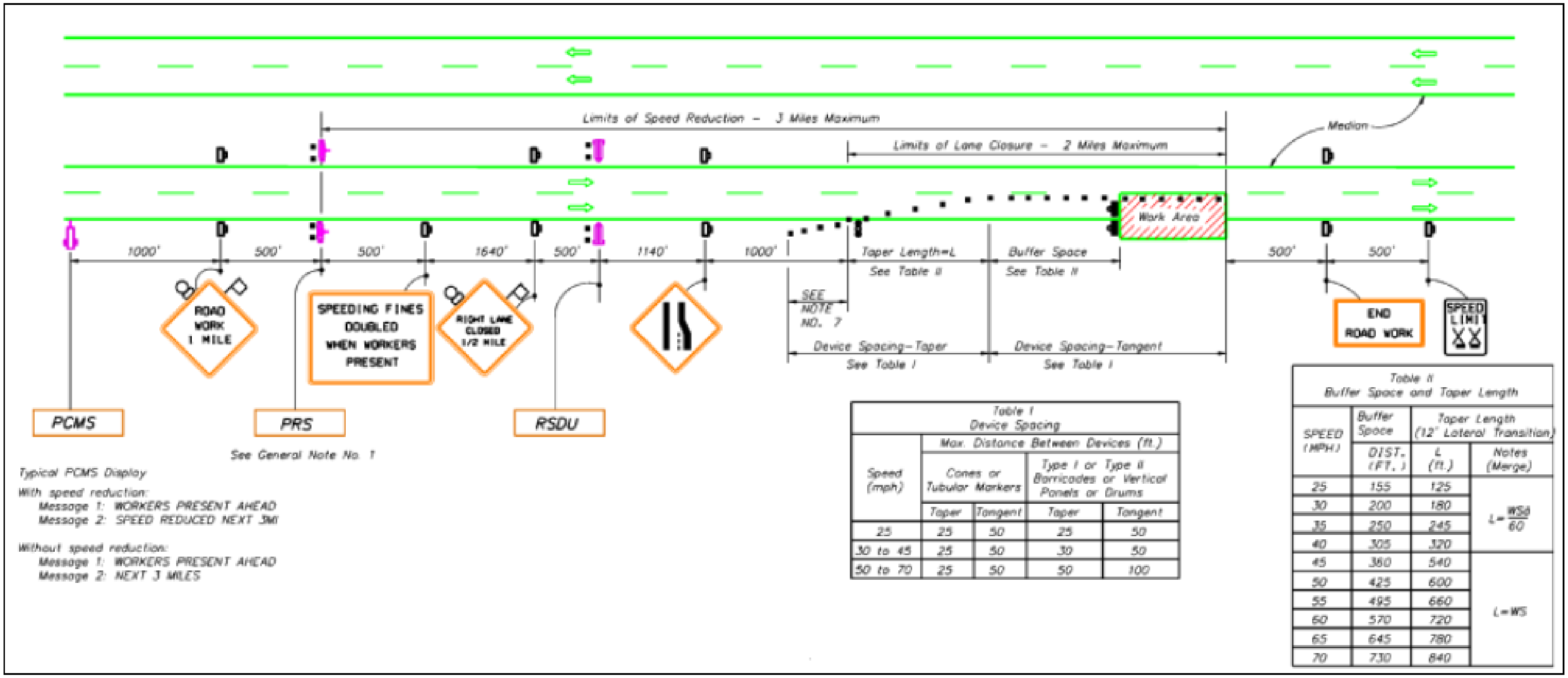

Table I
Device Spacing

Speed (mph)	Max. Distance Between Devices (ft.)			
	Cones or Tubular Markers		Type I or Type II Barricades or Vertical Panels or Drums	
	Taper	Tangent	Taper	Tangent
25	25	50	25	50
30 to 45	25	50	30	50
50 to 70	25	50	50	100

Table II
Buffer Space and Taper Length

SPEED (MPH)	Buffer Space	Taper Length (12' Lateral Transition)	
	DIST. (FT.)	L (ft.)	Notes (Merge)
25	155	125	$L = \frac{WS^2}{60}$
30	200	180	
35	250	245	
40	305	320	
45	360	540	$L = WS$
50	425	600	
55	495	660	
60	570	720	
65	645	780	
70	730	840	

Figure 3.1: Motorist Awareness System in Florida (Index 670 FDOT-Standards)

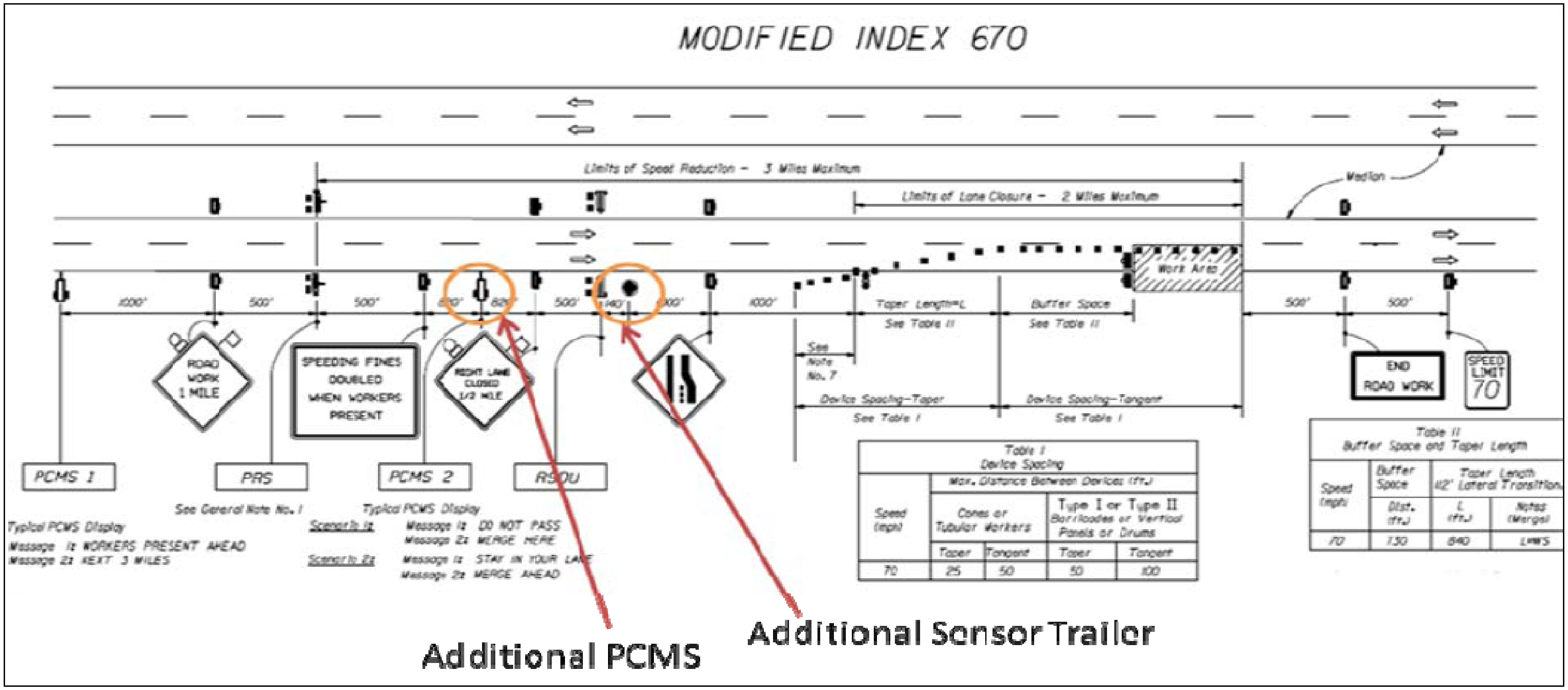

Figure 3.2: Modified Motorist Awareness System (SDLMS)

3.3. SDLMS System's Specifications

3.3.1. SDLMS System Components

The SDLMS shall consist of one set of the following equipment. The equipment is relocated as needed upon relocation of the work zone.

- ***Traffic detection station*** wirelessly linked to central computer base station. Traffic detection station is mounted to the PCMS that is a part of the system that shall be equipped with solar panel, deep cycle batteries and associated circuitry. The RTMS sensors can capture speed, volume, and occupancy.
- ***One central computer base station*** environmentally hardened and equipped with appropriate software and dedicated wireless communications to "link" with the traffic sensor station and PCMS. The computer base station shall be housed in a standard weather proof traffic-signal control cabinet, or other appropriate means, with provision for installation of the central communication antenna. 1 base station may be used for multiple directions of travel.
- ***Wireless communication links*** consisting of road-side remote stations, duly equipped with radio modems (for transmitting and receiving licensed UHF radio frequencies), micro- processors and antennae.
- ***PCMS*** remotely controlled via a central computer base station or central system controller.

The detection zones shall be located on the highway, distanced suitably to both gather traffic data and to cover the entire length of the desired stretch of the highway. The exact locations of all sensor stations shall be determined as part of an on-site communications analysis with project personnel.

3.3.2. SDLMS Features

The SDLMS features are as following:

- The software is modular with open architecture providing for future integration with other similar traffic monitoring systems and allowing detailed real-time monitoring of the status including communications-link operational status, current delay predicted for the roadway and current messages displayed on the PCMS. The software also provides options for various types of traffic data to meet the real-time speed control system needs.
- The SDLMS utilizes DOT compliant PCMS to convey real-time traffic condition information to motorists.
- The SDLMS operates continuously (24 hours, 7 days a week) for the duration of the project.

- Critical system operator control functions shall be password protected.
- The SDLMS is capable of acquiring traffic data and selecting motorist information messages automatically without operator intervention after system initialization.
- SDLMS is an independent stand alone unit with provision(s) for future integration with other traffic control / maintenance systems.
- The SDLMS traffic sensor's accuracy is not degraded by inclement weather of degraded visibility conditions including precipitation, fog, darkness, excessive dust, and road debris.
- All traffic data acquired by the DLMS are archived in a log file with time and date stamps.

3.3.3. SDLMS Traffic Data Acquisition

The SDLMS operation is based on real-time speed data acquired from the traffic detection zones with each data sample 'Time Stamped' to indicate currency of the message displayed. Software provided with the SDLMS system allows the operator to have options of various categories of traffic information to suit the needs of the speed control system as follows.

3.3.4. SDLMS Motorist Information Messages

The SDLMS message information characteristics are as following:

- Records of all motorist information messages displayed by the SDLMS are recorded in log files with time and date stamps.
- The SDLMS is capable of displaying default messages when traffic conditions, system algorithms, and user parameters do not dictate that an advisory message should be displayed.
- The SDLMS is capable of displaying separate, independent default messages, as well as separate, independent advisory messages on each PCMS.
- The SDLMS' default and advisory messages are capable of being automatically selected based on traffic conditions at a single traffic sensor point or at multiple traffic sensor points in combination.
- Default and advisory message content shall be programmable from the central base station.
- The SDLMS is capable of adjusting the thresholds for advisory message selection on an individual traffic sensor station basis from the central computer base station.
- For later use, the SDLMS is capable of storing messages created by an authorized user in overriding any default or automatic advisory message.

3.3.5. SDLMS Communications

The SDLMS communications characteristics are as following

- The SDLMS's communications system incorporates an error detection / correction mechanism to ensure the integrity of all traffic conditions data, motorist information messages.
- Any required configuration of the SDLMS's communications system is performed automatically during system initialization.
- Communications between central computer base station and any individual PCMS or traffic sensor station is independent through the full range of deployed locations and not rely upon communications with any other system.

3.3.6. SDLMS' Other Requirements

The SDLMS' other requirements are as following

- Remote sign operation via central computer base station using wireless licensed UHF radio frequencies in the range of 464 MHZ to 470 MHZ and provision(s) to install antenna
- NTCIP version 2 conformant and proprietary communications protocol, if any, shall be provided to the DLMS provider in proper format.
- Licenses / permissions to legally operate a wireless system must be owned by the DLMS system provider, where required.
- The central computer base station shall be housed at a suitable location, to facilitate wireless communications, and in a suitable enclosure with AC power, internet access or a minimum of a reliable, dedicated telephone line.

3.3.7. Remote Traffic Microwave Sensor

RTMS are radar-based, non-intrusive, advanced sensors for the detection and measurement of traffic on roadways. They are known to be easy to install, remove, and maintain without traffic disruption. As shown in Figure 3.3, the RTMS are pole-mounted on the side of the road. They can collect the per-lane presence, volume, vehicle classification, occupancy, and speed in up to 8 user-defined detection zones.

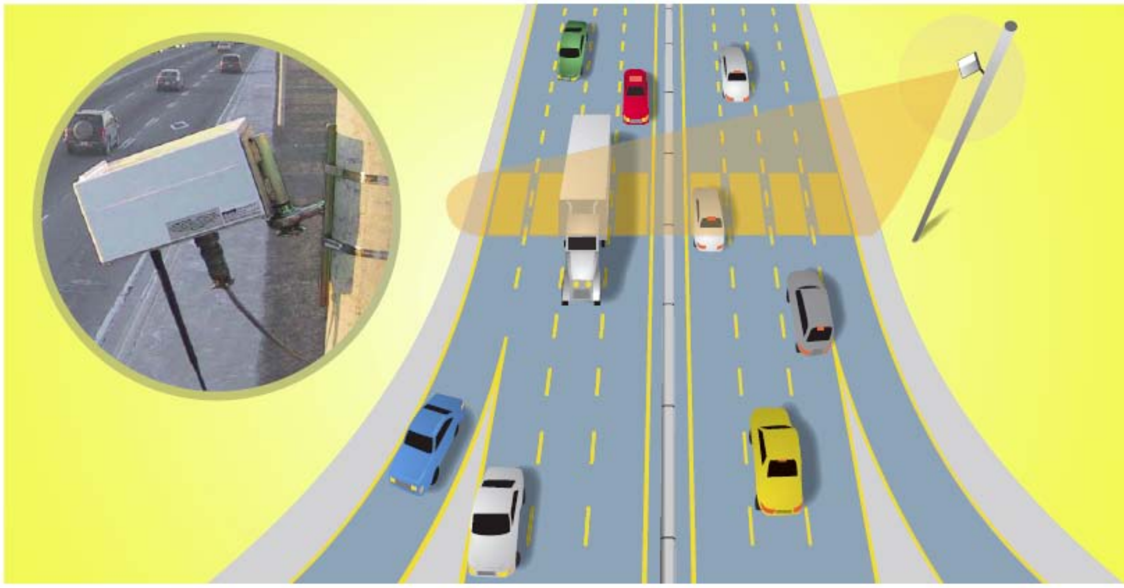

Figure 3.3: Remote Traffic Microwave Sensors

3.4. SDLMS field setup

3.4.1. SDLMS Preparation

The SDLMS preparation is shown in Figures 3.4, 3.5, 3.6 and 3.7. The University of Central Florida (UCF) team setup the SDLMS at the site and the details are as following:

- UCF took the sensor trailer to the site Feb 7, 2008.
- The new chip received from VERMAC was installed in the VERMAC PCMS.
- The communication system including antennas and processing unit was installed
- The RTMSs were mounted on the PCMS and the sensor trailer
- The RTCP counter was installed in the first PCMS

3.4.2. SDLMS Testing

The UCF team tested the SDLMS at the site and the details are as following:

- The communication between the sensor trailer and the PCMS was tested (Feb 16, 2008)
- The RTMS' were tested including the proper leveling of the sensor and the calibration.
- The UCF team was trained on the calibration of the RTMS'.

- The UCF team was trained on the daily setup of the DLM system including the proper leveling of the sensor trailer and the instantaneous testing of the communication system.
- UCF was also trained on extracting the data from the RTMS'.

It should be noted that the communication system on the additional PCMS rely on the proper power supply from the latter. The communication between the PCMS and the sensor trailer may fail if the batteries of the PCMS are not properly charged.

Figure 3.4: PCMS Chip Modification

Figure 3.5: Antenna Installation

Figure 3.6: Sensor Trailer Setup

Figure 3.7: SDLMS Controller

3.4.3. RTMS Calibration

The RTMS was calibrated on a daily basis upon reinstallation. The sensor trailer was leveled in a way that the pole on which the RTMS is mounted is perpendicular to the road. The first step in the calibration consists of creating the capturing or sensing zones as shown in Figure 3.8. In our case we had two lanes therefore two sensing zones were created. Sequentially, the calibration of the speeds is implemented. After completing the calibration process the system will be set to operate.

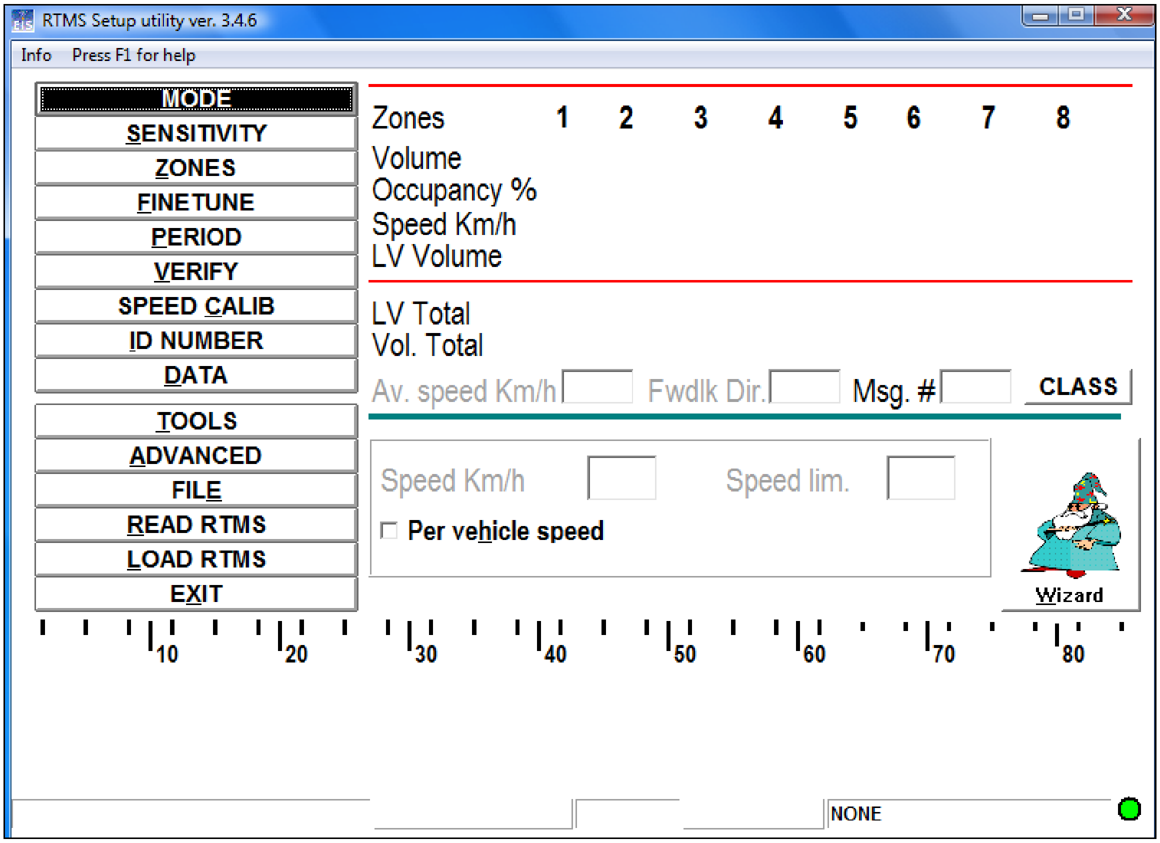

Figure 3.8: RTMS Calibration.

3.4.4. System Check-up

The SDLMS provided by IRD, Inc. contains an application that allows us to check on the performance of the system. The system contains an “Adaptir” map (shown in Figure 3.9) that displays the location of the sensor trailer and the PCMS on the map and shows a green light for the correct wireless communication between the sensor (RTMS) and the PCMS. In case there is a miscommunication (wireless defect) the Adaptir map will display a red light and display an error message.

Figure 3.9: Adaptir Map

3.5. SDLMS Operation

The SDLMS operation is based on real-time speed data acquired from the traffic detection zones with each data sample (time-stamped over 2 minutes) to indicate currency of the message displayed. The RTMS collects the average speed of the vehicles passing through the detection zones over 2-minute time intervals. The SDLMS operates under two modes; the passive mode (not activated) and the active mode (activated). Under the passive mode the additional PCMS is set to display a flashing "CAUTION/CAUTION" message for both the early and late SDLMS. Under the active mode, the PCMS displays "DO NOT PASS" followed by "MERGE HERE" alternately for the early SDLMS and "STAY IN YOUR LANE' followed by "MERGE AHEAD" alternately for the late SDLMS (as shown in Table 3.1). The early and late SDLMS are activated once the average speed over any 2-minute time interval drops below 50mph. The SDLMS will be deactivated (passive mode) once the average speed over the next time stamp goes over 50 mph. It should also be noted that the minimum activation time of the PCMS was set for 5 minutes.

Table 3.1: SDLMS' Active and Passive Messages

Early Merge

Activated			NOT Activated	
DO	MERGE			
NOT	HERE		CAUTION	CAUTION
PASS				

Late Merge

Activated			NOT Activated	
STAY	MERGE			
IN YOUR	AHEAD		CAUTION	CAUTION
LANE				

3.6. Project Communication

The UCF research team communicated with multiple parties to conduct this project (see Figure 3.10):

1. IRD Inc. provided the SDLMS system
2. Smart Technologies provided the communication system and system training
3. Highway technologies provided the PCMS through FDOT.
4. VERMAC provided the updated PCMS chip to match the system's protocol.
5. A Florida licensed professional engineer (consultant) signed and sealed the modified MOT plans.
6. FDOT project manager along with FDOT district 5 and UCF selected sites for data collection.
7. UCF, local operation office, and road rangers were constantly in touch during the data collection.

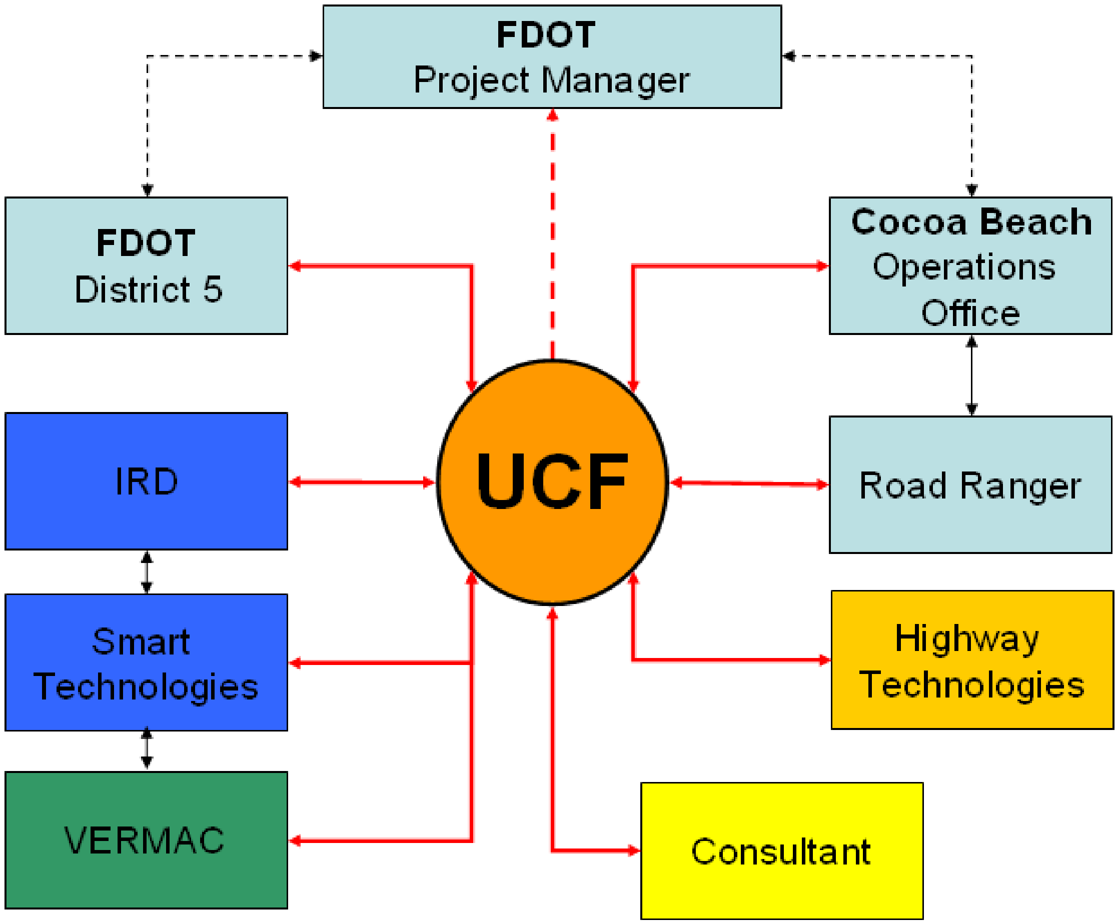

Figure 3.10: Project Communication Flowchart

4. MALABAR FL DATA COLLECTION AND ANALYSES

4.1. Data Collection

4.1.1. Site Location

The selected site was located on Interstate-95 in Malabar, Florida as shown in Figure 4.1. I- 95 is two-lane per direction limited access rural freeway with 70 mph speed limit (reduced to 60 mph during work). The work zone consisted of a resurfacing and milling job on the south bound of I-95 on a 13 mile stretch. A two to one lane closure configuration was adopted and the work zone moved on a daily basis covering a length of approximately three miles per day. Data was collected on homogenous basic freeway segment of I-95 with no on/off ramps.

4.2.1. Data Collection Methodology

Four Digital Camcorders were set in the field labeled C-1, C-2, C-3, and C-4 as shown in Figure 4.2. To synchronize the camcorders spatially (i.e. upon daily relocation), C-1 was always located behind the first PCMS, C-2 was always located behind the lane drop static signs, C-3 was always located behind the arrow panel, and C-4 was always located at the end of the lane closure. All four camcorders were started at the same time to synchronize the temporal events and flow of vehicles. Data was collected on the same site for the MAS, early SDLMS, and late SDLMS for two days each. From C-1, C-2, C-3, and C-4, per-lane vehicle counts including vehicle classification were extracted in five minutes intervals in the laboratory. The zone between C-1 and C-2 is identified as zone 1 and the zone between C-2 and C-3 is identified as zone 2. The difference between the vehicle counts (including vehicle classification) in the closed lane between C-1 and C-2 is the number of lane changes made in zone 1. The remaining vehicle counts (including vehicle classification) remaining in the closed lane at C-2 is the number of lane changes in zone2.

The RTMS was temporally synchronized with C-1, C-2, C-3, and C-4 and the PCMS activation time (recorded by the RTMS) was extracted and concatenated temporally to the vehicle count data. From C-1 the demand volume for the work zone was determined. From C-4 the throughput of the work zone was determined. Under the standard MAS configuration, data was collected on February 11th and 12th 2008, under the early SDLMS data was collected on March 17th and 18th 2008, and under the late SDLMS data was collected on March 27th and 28th, 2008. There were several difficulties engaged in the data collection process. In fact, for short term moving work zones, there exist inherent logistic and operational difficulties. For instance, the work, hence data collection was cancelled and/or interrupted unexpectedly multiple times due to adverse weather conditions that are crucial for resurfacing and milling jobs. Work was also unexpectedly cancelled on several occasions without prior notice due to contractor-related logistic issues. Moreover, the freeway shoulders were narrower at some locations which made the installation of the SDLMS equipment almost impossible. It is recommended that a good communication/planning be established between the researcher team and the work zone crew (construction manager) for future data collection on short term moving work zones.

4.2. Data Analyses

Roadway capacity in which a work zone is located is lower than the normal operating conditions. The impact of the early and late SDLMS on the work zone capacity is studied by comparing the capacity of the work zone under the MAS traffic (control) to the capacity of the work zone under the early SDLMS (test1) and late SDLMS (test2). It should be noted that different researchers, as mentioned by Heaslip et al. *(37)*, have different definitions of work zone capacity. Some researchers *(13, 37, 41 and 49)* measured the mean queue discharge flow rate as work zone capacity when the upstream of work zones was in sustained congested traffic flow, while other researchers *(12, 39 and 63)* defined the work zone capacity as the traffic flow at the onset of congested traffic conditions. Ping and Zhu *(63)* studied the work zone capacity under the three different scenarios is determined as the queue discharge flow rate or throughput volume under queuing/congested conditions. The onset of congestion is determined by C-3 shown in Figure 4.2.

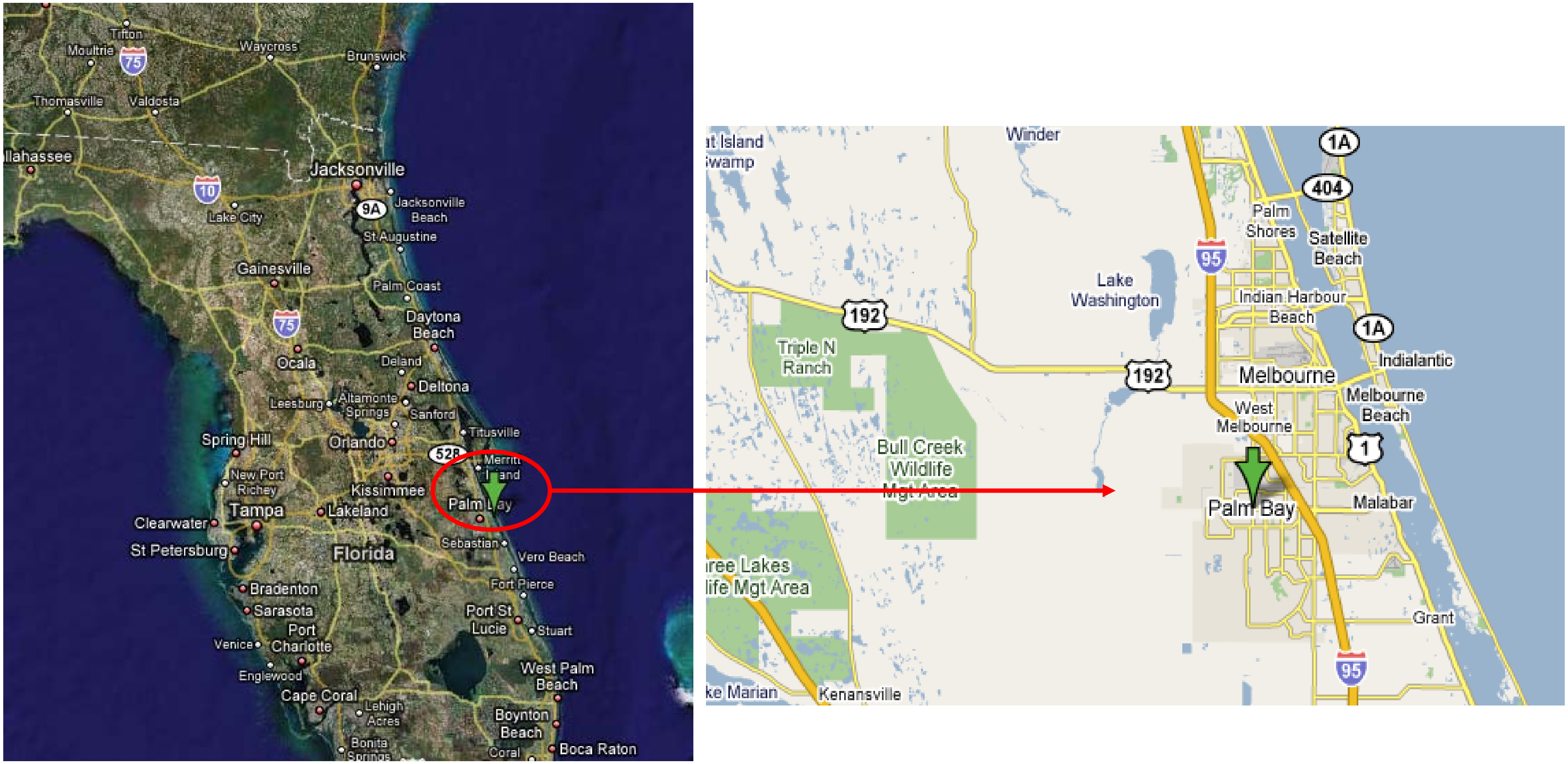

Figure 4.1: Data Collection Site, Malabar, Florida

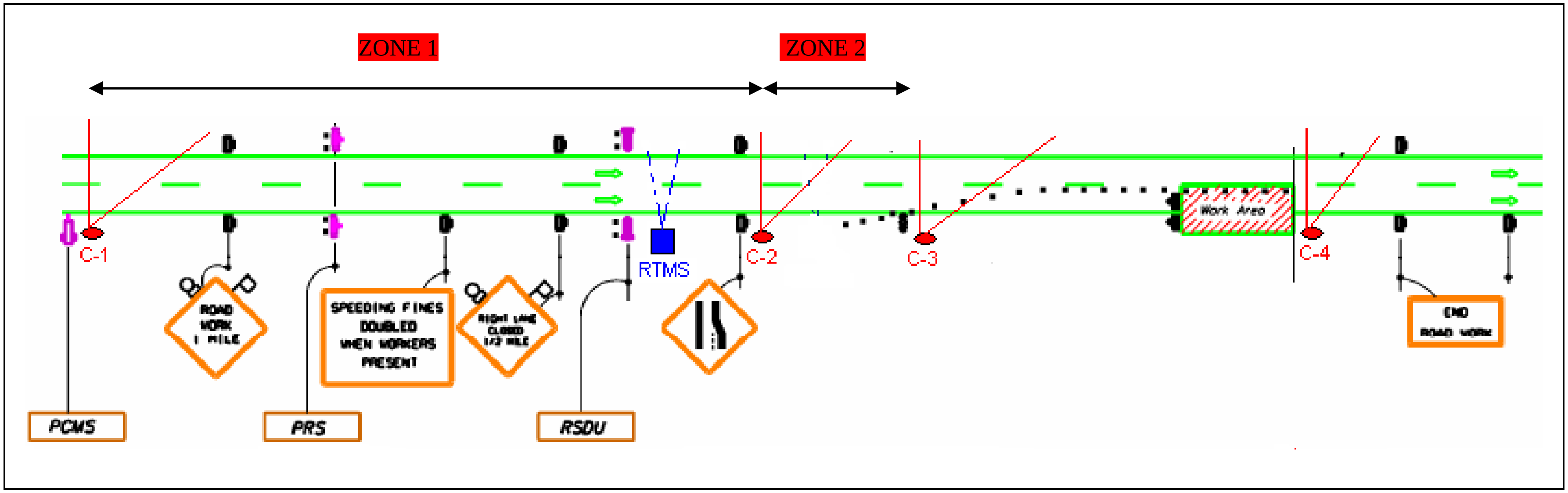

Figure 4.2: Camcorders Location

4.2.1. Work Zone Capacity

Table 4.1 summarizes the data extracted from C-1, C-2, C-3, and C-4. As shown by Table 4.1, the mean and maximum capacities of the early SDLMS are the highest among the three MOT treatments. The mean and maximum capacities of the conventional MAS system are 881 veh/hr and 1092 veh/hr respectively. The mean and maximum capacities of the early SDLMS are 970 veh/hr and 1272 veh/hr correspondingly. The mean and maximum capacities of the late SDLMS are 896veh/hr and 1093 veh/hr in that order.

Table 4.1: Data Summary Statistics

MOT TYPE	Variable	Unit	Mean	Standard Deviation	Min.	Max.
Conventional MAS	Capacity	Veh/hr	881	120	624	1092
	Car Lane changes in Zone1	Pc/hr	143	118	84	324
	Truck Lane changes in Zone1	Trk/hr	57	46	84	120
	Car Lane changes in Zone2	Pc/hr	51	53	48	168
	Truck Lane changes in Zone2	Trk/hr	16.8	30	12	132
	% Trucks	N / A	0.151	0.060	0.024	0.258
	% Car Lane Changes in Zone 1	N / A	0.663	0.247	0.125	0.957
	% Truck Lane Changes in Zone 1	N / A	0.796	0.192	0.389	1.000
Early SDLMS	Capacity	Veh/hr	970	135	696	1272
	Car Lane changes in Zone1	Pc/hr	293	102	96	516
	Truck Lane changes in Zone1	Trk/hr	92	81	24	312
	Car Lane changes in Zone2	Pc/hr	108	62	12	312
	Truck Lane changes in Zone2	Trk/hr	23	26	24	96
	% Trucks	N / A	0.055	0.136	0.136	0.357
	% Car Lane Changes in Zone 1	N / A	0.675	0.071	0.071	1.000
	% Truck Lane Changes in Zone 1	N / A	0.769	0.000	0.000	1.000
Late SDLMS	Capacity	Veh/hr	896	111	696	1092
	Car Lane changes in Zone1	Pc/hr	274	95	60	516
	Truck Lane changes in Zone1	Trk/hr	33	24	24	84
	Car Lane changes in Zone2	Pc/hr	100	51	12	192
	Truck Lane changes in Zone2	Trk/hr	12	13	0	48
	% Trucks	N / A	0.246	0.054	0.136	0.357
	% Car Lane Changes in Zone 1	N / A	0.519	0.157	0.250	1.000
	% Truck Lane Changes in Zone 1	N / A	0.741	0.289	0.000	1.000

Also from Table 4.1, the mean number and mean percentage of lane changes in zone 1 for cars and trucks are the highest for the early SDLMS and the lowest for the late SDLMS. These average numbers of lane changes are taken for all times including when the additional PCMS is not activated for the early and late SDLMS. The mean number and percentage of passenger cars changing lanes in zone 1 for the early SDLMS are 293pc/hr and 67.5% respectively (92Trk/hr, 76.9% for trucks). The mean and percentage of passenger cars changing lanes in zone 1 for the late SDLMS are 274 pc/hr and 51.9% respectively (33 Trk/hr, 74.1% for trucks). The mean and percentage of passenger cars changing lanes in zone 1 for the conventional MAS are 143 pc/hr and 66.3% in that order (57Trk/hr, 79.6% for trucks). These results indicate that some drivers are complying with the messages displayed by the additional PCMS in the early and late SDLMS.

During the early and late SDLMS, the additional PCMS may not be activated when the average detected speed does not fall below the preset threshold speed (50 mph). Therefore, one should compare the capacities of the early and late SDLMS with the conventional MAS only when the additional PCMS is activated, hence displaying the lane merging advisory messages. Therefore, a new variable (labeled ACT) is derived to reflect this issue. This variable (ACT) consists of four levels; early and late SDLMS not activated, early SDLMS activated, late SDLMS activated, and conventional MAS. A multiple linear regression model is conducted to explore the effect of the MOT plan type and other collected variables on the work zone capacity. Table 4.2 shows the results of the regression model.

From Table 4.2, the ACT shows significant effect on the capacity (queue discharge) of the work zone. In particular, the early SDLMS treatment affects positively (parameter estimate= 10.312) and significantly the capacity of the work zone compared to the conventional MAS maintenance of traffic plan. The other variables included in the model do not have a statistical significant effect on the work zone capacity at 0.05 significance level.

Table 4.2: Multiple Linear Regression Results

ANOVA and Parameter Estimates

Parameter	Categories	Estimate	Standard Error	t Value	Pr > |t|
Intercept	N/A	78.447	6.173	12.710	<.0001
% PC lane changing in zone1	N/A	-9.514	5.546	-1.720	0.089
%TRK lane changing in zone1	N/A	1.965	4.037	0.490	0.628
%TRK	N/A	-2.010	19.303	-0.100	0.917
ACT	Late SDLMS	4.507	4.890	0.920	0.359
	Early SDLMS	10.312	3.520	2.930	0.004
	NOT ACTIVATED	4.300	3.406	1.260	0.209
	CONVENTIONAL MAS	0.000	.	.	.

Overall ANOVA

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	6	1656.106	276.0177	2.45	0.0291
Error	109	12268.4	112.5542		
Corrected Total	115	13924.51			

4.2.2. Travel Time

Camcorders C-1 and C-4 were used to observe the travel time through the work zone. Past literature *(58 and 65)* documented methods to determine the minimum required sample size for travel time runs to achieve reliable and accurate results. The following Equation from May *(46)* is used to determine the number of runs required:

$$n = \left\{ \frac{\hat{\sigma} x * Z}{\varepsilon} \right\}^2$$

Where,

N = Estimated sample size for number of runs at the desired precision and level of confidence

σ = Preliminary estimate of the population standard deviation for average travel speed among the sample runs

Z = Two-tailed value of the standardized normal deviate associated with the desired level of confidence (at a 95% confidence interval, Z=1.96)

ε = Acceptable Error (±3 mph)

According to Oppenlander *(58)* the allowable errors range between ±1 mph to ±3 mph for 'before and after' entailing operational improvement of roadways. In this study the allowable error is assumed to be ±3 mph. During the MAS only (before period) 45 travel time runs were determined. The resulting mean and standard deviation for the average travel speed through the work zone were determined to be 37.5 mph and 8.74 mph respectively. The resulting minimum required sample size of travel time runs is determined by the above Equation to be:

$$n = \left\{ \frac{8.74 * 1.96}{3} \right\}^2 = 33$$

The actual number of travel time runs for the MAS, early SDLMS, and late SDLMS exceeded the minimum required number of runs (nMAS=63; nearly=67; nlate= 69). An analysis of variance of the travel time observations for the MAS, early SDMLS, and late SDLMS indicated the variances were not equal. Therefore, the unequal variance t-test was performed to determine whether there exists a significant difference in the travel times between the three treatments. The average travel time for the MAS, early and late SDMLS are 3.97minutes, 3.87 minutes, and 3.78 min respectively and the resulting *p*-values are 0.302 (comparing early SDLMS to MAS), 0.532 (comparing late SDLMS to MAS), and 0.539 (comparing early and late SDMLS) indicating no statistical significant difference between the travel times of MAS, early and late SDLMS. Table 4.3 summarizes the travel time comparison between the three treatments.

Table 4.3: Travel Time Comparison

	Mean Travel time	P-value	Significant
MAS Vs. Early SDLMS	3.97 min. Vs. 3.87 min	0.302	NO
MAS Vs. Late SDLMS	3.97min Vs. 3.78 min	0.532	NO
Early SDLMS Vs. Late SDLMS	3.87 min Vs. 3.78 min	0.539	NO

4.3. Conclusions

The capacity of the work zone under the control and test MOT plans was used as a measure of effectiveness to explore the impact of the early and late SDLMS on work zones. The regression model showed that the early SDLMS enhance work zone capacity significantly from 881 veh/hr to 970veh/hr. The late form of SDLMS increased the mean capacity from 881 veh/hr to 896 veh/hr, however this increase was not statistically significant.

The travel time through the work zone under the control and test MOT plans were examined. The average travel time for the MAS, early and late SDMLS are 3.97 minutes, 3.87 minutes, and 3.78 min respectively and did not result in statistically significant difference. This indicates that the simplified dynamic early and late merge did not affect the travel time through the work zone.

The number and percentage of lane changes in zone 1 were the highest for the early SDLMS and the lowest for the late SDLMS. This indicates that drivers are complying with the messages displayed by the additional PCMS. It was noted during data collection, for the early SDLMS, that drivers usually comply with the messages displayed by the PCMS. However, it was also observed that when a vehicle uses the closed lane to pass vehicles in the queue and merge into the open lane ahead of them, a platoon of vehicles follows this vehicle which defeats the purpose of the early SDLMS.

5. PALM BEACH FL DATA COLLECTION AND ANALYSES

5.1. Data Collection

The work zone consisted of a resurfacing and milling job on the south bound of I-95 on a 5 mile stretch. A three to two lane closure configuration was adopted and the work zone moved on a daily basis covering a length of approximately one mile per day. Similar to the Palm Bay site, four digital camcorders were set in the field labeled C-1, C-2, C-3, and C-4 as shown in Figure 5.1. To synchronize the camcorders spatially (i.e. upon daily relocation), C-1 was always located behind the first PCMS, C-2 was always located behind the additional PCMS, C-3 was always located by the beginning of the lane closure, and C-4 was always located at the end of the lane closure. All four camcorders were started at the same time to synchronize the temporal events and flow of vehicles. Data was collected on the same site for the MAS, early SDLMS, and late SDLMS for two days each. From C-1, C-2, C-3, and C-4, per-lane vehicle counts including vehicle classification were extracted in 5 minutes intervals in the laboratory. The zone between C-1 and C-2 is identified as zone 1 and the zone between C-2 and C-3 is identified as zone 2. The difference between the vehicle counts (including vehicle classification) in the closed lane between C-1 and C-2 is the number of lane changes made in zone 1. The remaining vehicle counts (including vehicle classification) remaining in the closed lane at C-2 is the number of lane changes in zone 2.

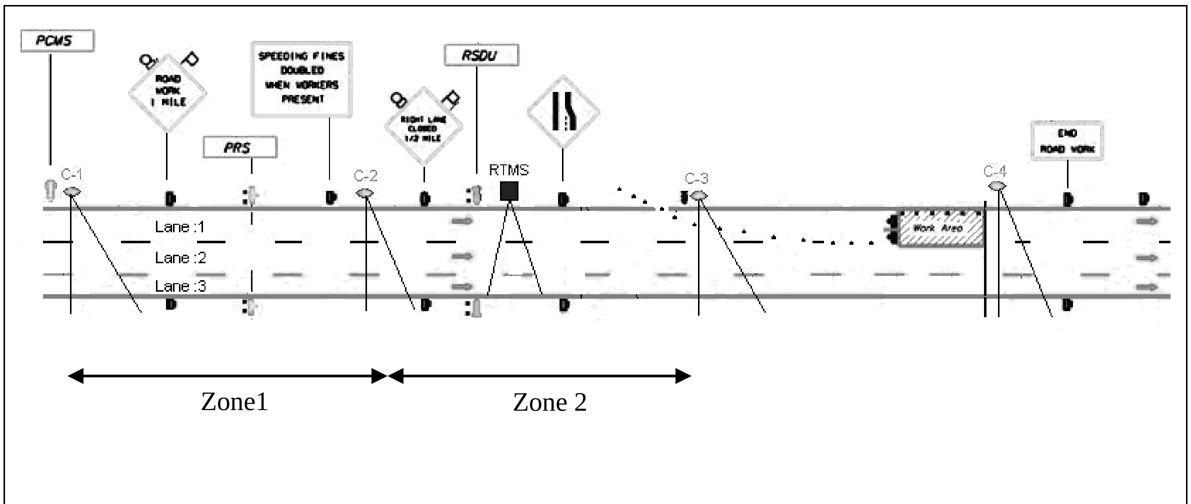

Figure 5.1: Cameras Location

5.2. Safety MOE

The speed fluctuation at the location of the RTMS is taken as the safety measure of effectiveness. The speed fluctuation is the difference in average speed over two-minute consecutive time intervals. If the speed fluctuation is high one can conclude that the risk of accident is higher. Figures 5.2, 5.3, and 5.4 show the distribution of the speed fluctuations under the MAS, early, and late merge treatments in that order. Lane 1 is the closed lane, lane 2 is the middle lane and lane 3 is the outer lane. A negative speed fluctuation means a speed drop between two consecutive time intervals and a positive speed fluctuation means a speed increase between two consecutive time intervals. Examining Figures 5.2, 5.3 and 5.4, one can conclude that work zone under the MAS regime undergoes the highest speed fluctuation. The range of speed fluctuation for the closed lane (lane 1) under the MAS MOT plans varies between -48mph to 47mph, compared to a range of -9 mph to 7 mph for the dynamic early merge and a range of -5 mph to 3 mph to the dynamic late merge. The range of speed fluctuation for the middle lane (lane 2) varies from -12.5 mph to 17.5 mph for the MAS MOT plans compared to -8 mph to 5 mph for the dynamic early merge and -6 mph to 5 mph for the dynamic late merge. As for the outer lane (lane 3) the speed fluctuation varies from -66 mph to 68 mph for the MAS system compared to a range of -13 mph to 10 mph for the dynamic early merge and a range of -5 mph to 7 mph for the dynamic late merge (See Figures 5.1, 5.2, and 5.3). Figure 5.5 compares the speed fluctuations for lanes 1, 2, and 3 under different demand volumes for the three different MOT types. Looking at MAS, the speed fluctuation for lane 1 (closed lane) and lane 3 (the outer lane) are the highest for demand volumes below 1,500 veh/hr. Figure 5.5 shows that the speed fluctuation for lane 2 is fairly stable under different demand volumes. Looking at early and late charts from Figure 5.5, one can conclude that the speed fluctuation is fairly similar under all demand volumes. Finally one can conclude that the speed fluctuates the most under the MAS system.

The next step was to examine the speed fluctuations in each lane under different demand volumes. To complete this task, the demand volumes were split into 5 categories. The first demand volume labeled v1 varies between 0 and 500 veh/hr. The second demand volume labeled v2 varies between 501 and 1000 veh/hr. The third demand volume v3 category varies between 1001 and 1500 veh/hr. The fourth demand volume v4 category ranges from 1501 and 2000 veh/hr and the fifth demand v5 is greater than 2001 veh/hr.

Table 5.1 shows the t-test results for comparing fluctuation means in each lane under different volumes. Table 5.2 displays the means of speed fluctuations under different volumes. In table 5.1 the statistically significant difference between the speed fluctuation means (p-value<0.05) are highlighted in grey. As shown by Table 5.2, the mean speed fluctuation in lane 1 (closed lane) was the highest under the MAS system for all demand volumes. The P-values of the differences in those means are statistically significant (highlighted in grey). This means that the dynamic late merge and the dynamic early merge have lower speed fluctuations in the closed lane under all demand volumes compared to the MAS system. Comparing the dynamic early merge and the dynamic late merge mean speed fluctuations in the closed lane, Table 5.2 shows that the mean speed fluctuations for the early merge are lower than those of the late merge under demand all demand volumes. However, Table 5.1 shows that the difference in the mean speed fluctuation is only statistically significant under demand volume ranging between 0 and 500 veh/hr.

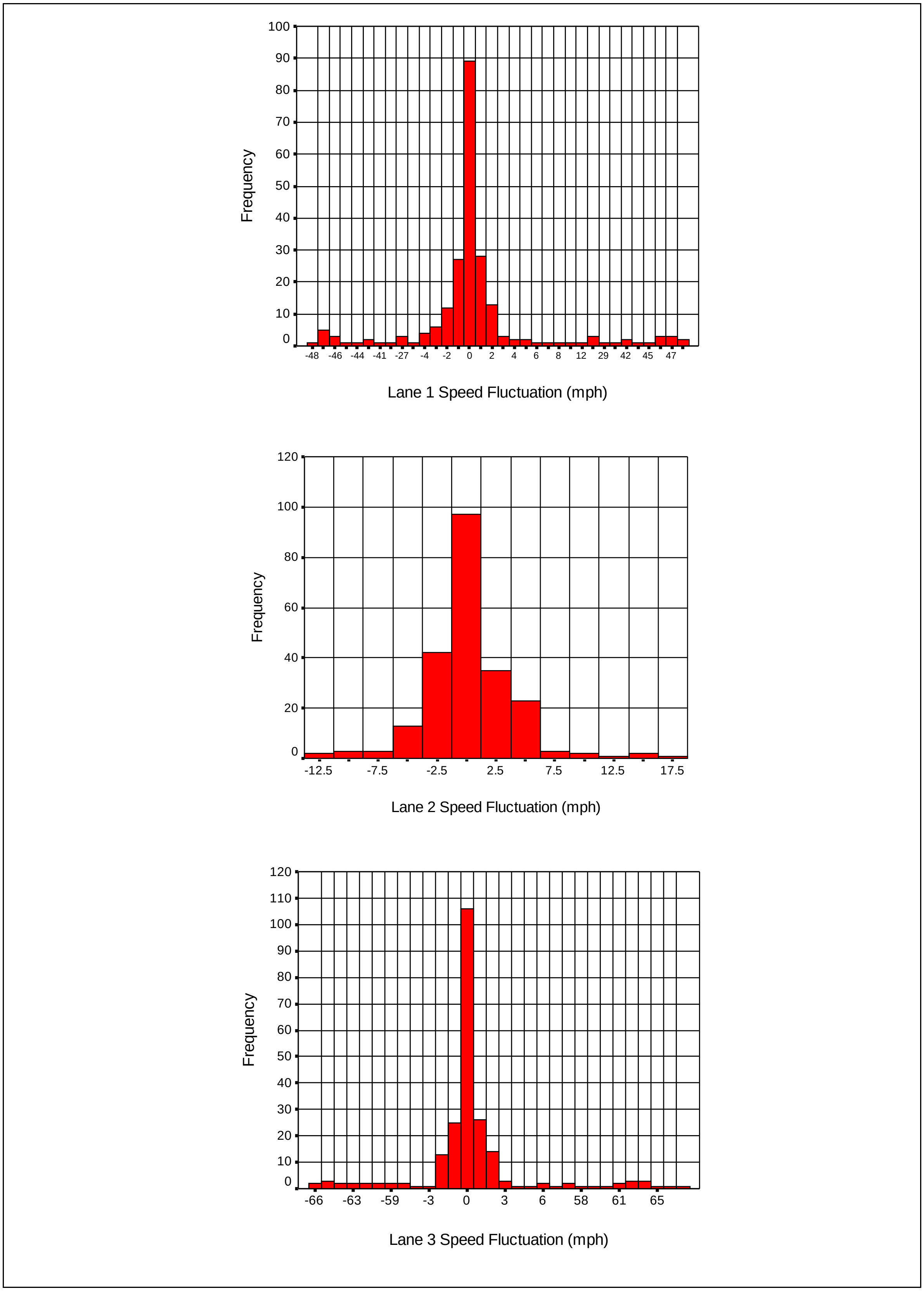

Figure 5.2: MAS Speed Fluctuation per Lane

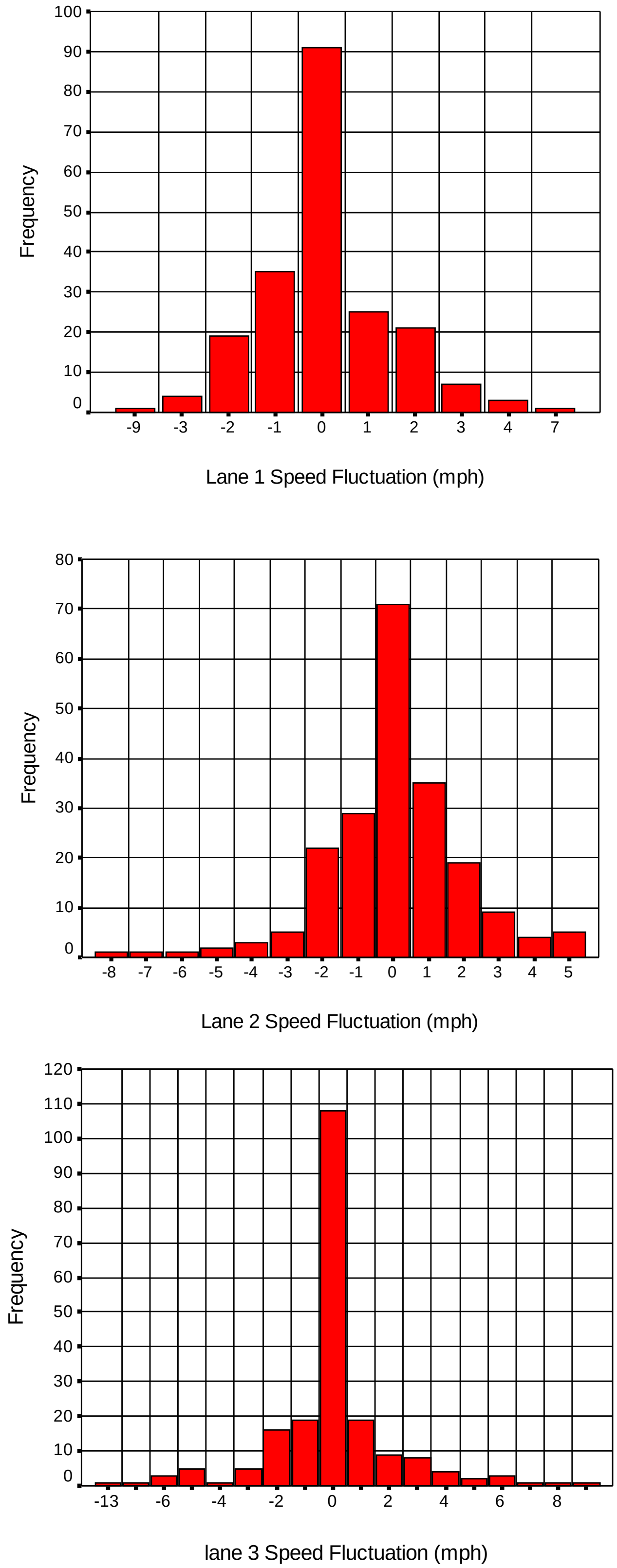

Figure 5.3: Early Merge Speed Fluctuation per Lane

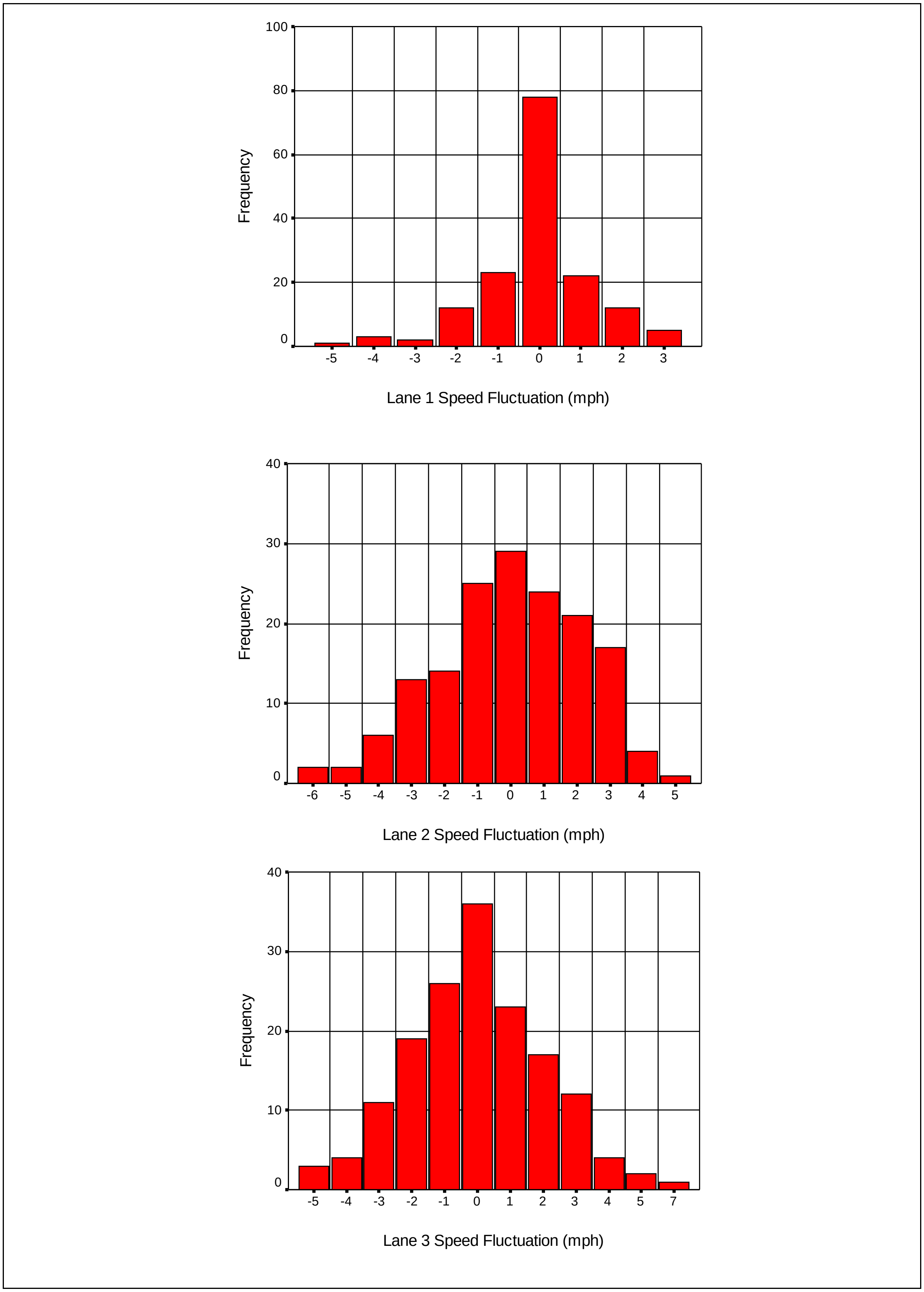

Figure 5.4: Late Merge Speed Fluctuation per Lane

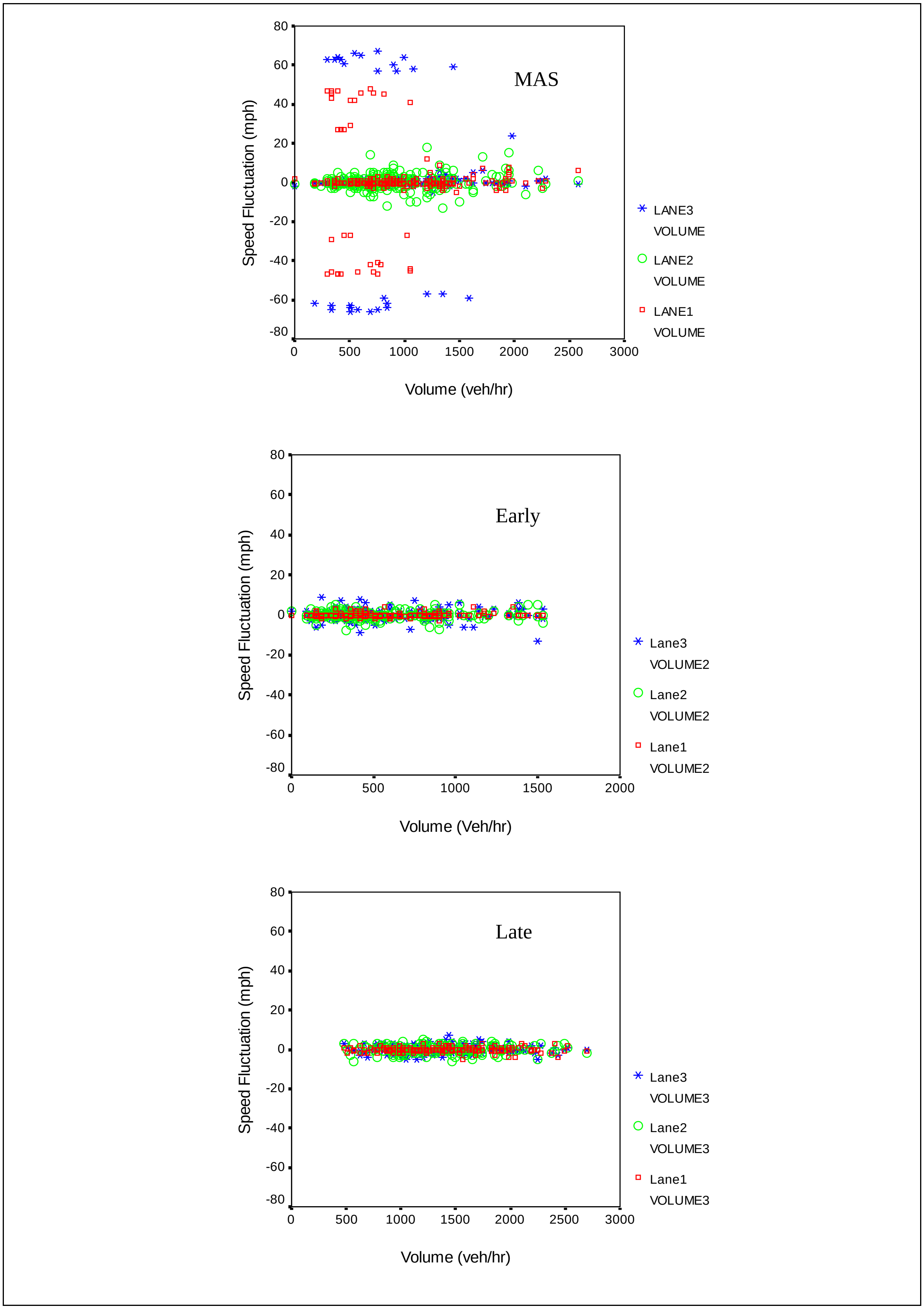

Figure 5.5: Speed Fluctuation for MAS/Early/Late Under Different Volumes

Table 5.1: P-value for Mean Differences of Speed Fluctuation

	P-value		
	Late Merge Vs. MAS	Early Merge Vs. MAS	Early Merge Vs. Late Merge
lane1 v1	0.2188	0.0000	0.0153
lane1 v2	0.0277	0.0052	0.5597
lane1 v3	0.0054	0.0850	0.6927
lane1 v4	0.0005	0.0384	0.0733
lane1 v5	0.4236	N/A	N/A
lane2 v1	0.3267	0.9766	0.3257
lane2 v2	0.0715	0.0260	0.9221
lane2 v3	0.0006	0.0157	0.4330
lane2 v4	0.0012	0.4247	0.1242
lane2 v5	0.0286	N/A	N/A
lane3 v1	0.0099	0.0000	0.9162
lane3 v2	0.0275	0.0111	0.0572
lane3 v3	0.0633	0.3343	0.1705
lane3 v4	0.0831	0.9388	0.0202
lane3 v5	0.9849	N/A	N/A

Table 5.2: Mean of Speed Fluctuations Under Different Volumes

	Mean Speed Fluctuation (mph)		
	Late Merge	Early Merge	MAS
Lane1 v1	1.50	0.32	16.94
Lane1 v2	0.74	0.63	5.75
Lane1 v3	0.72	0.62	4.78
Lane1 v4	0.98	0.00	2.63
Lane1 v5	1.56	N/A	2.20
Lane2 v1	1.50	1.24	1.22
Lane2 v2	1.69	1.63	2.39
Lane2 v3	1.72	1.43	3.49
Lane2 v4	1.95	2.50	4.32
Lane2 v5	1.50	N/A	3.40
Lane3 v1	2.00	1.56	16.17
Lane3 v2	1.51	1.93	9.27
Lane3 v3	1.79	2.52	5.88
Lane3 v4	1.52	4.75	5.32
Lane3 v5	1.38	N/A	1.40

Looking at the speed fluctuations in the middle lane (lane 2), Table 5.2 shows that the mean speed fluctuations are the highest for the MAS system compared to dynamic early merge and dynamic late merge under all demand volumes. However, Table 5.1 shows that the mean speed fluctuations under the MAS are significantly higher than the mean speed fluctuations under the dynamic late merge only for volumes for volumes greater than 1500 veh/hr (and marginally at volumes between 1000 and 1500 veh/hr). Table 5.1

also shows that the mean speed fluctuations under the MAS are significantly higher than the mean speed fluctuations under the dynamic early merge system for volumes ranging between 500 and 1500 veh/hr. Comparing the mean speed fluctuations under the dynamic early merge and the dynamic late merge Table 5.2 shows that the mean speed fluctuations are lower for the dynamic early merge. However, there is no significant difference between the speed fluctuations in the middle lane (Lane 2).

Looking at the speed fluctuations in lane 3 (outer lane), Table 5.2 shows that the mean speed fluctuations are the highest under the MAS system compared to the dynamic early merge and the dynamic late merge under all volumes. However, Table 5.3 shows that the mean speed fluctuations for the MAS system is significantly higher than the mean speed fluctuation for dynamic early and dynamic late merge for volumes under 1000 veh/hr. Moreover, Table 5.1 shows a marginal significance indicating that the mean speed fluctuation for the late merge is lower than the mean speed fluctuation for the MAS system for volumes ranging 1000veh/hr to 2000 veh/hr. Comparing the mean speed fluctuations between the dynamic early and dynamic late merge, Table 5.2 shows that the means speed fluctuations are lower for the dynamic late merge under volumes higher than 500 veh/hr. However, Table 5.1 shows that the mean speed fluctuation for the dynamic late merge is significantly lower than the mean speed fluctuation for the dynamic early merge for demand volumes ranging between 1500veh/hr and 2000veh/hr.

Table 5.3 summarizes the safety MOE for each lane under different MOT plans. The colors compare the dynamic early and late merge to the MAS. The green color means that the dynamic early or late merge is better than the MAS. The yellow color means that the difference is not significant, and the blue color means that difference is unknown (small sample size). To compare dynamic early and late merge we used the letters E and L. As shown by the Table 5.3, the early SDLMS was better than the late SDLMS for L1V1 and the late SDLMS was better than the early SDLMS for L3V4.

Table 5.3: Comparison of Early SDLMS, Late SDLMS and MAS for Safety

Late and Early Compared to MAS															
	V1			V2			V3			V4			V5		
	Lane 1	Lane2	Lane3	Lane1	Lane2	Lane3	Lane1	Lane2	Lane3	Lane1	Lane2	Lane3	Lane1	Lane2	Lane3
Dynamic Early Merge	E														
Dynamic Late Merge												L			

5.3. Operational MOE

Similar to the Palm Bay site analysis, the work zone throughput is taken as an operational measure of effectiveness. Roadway capacity in which a work zone is located is lower than the normal operating conditions. The impact of the early and late SDLMS on the work zone capacity is studied by comparing the capacity of the work zone under the MAS traffic (control) to the capacity of the work zone under the early SDLMS (test1) and late SDLMS (test2). The onset of congestion is determined by C-3 shown in Figure 5.1.

Table 5.4 summarizes the variables taken into account to analyze the operational aspects of the work zone under three different regimes (MAS, early and late SDLMS). The maximum throughput for the work zone under the MAS system is 2,730 veh/hr, the maximum throughput under the dynamic early merge is 1890 veh/hr, and the maximum throughput under the late merge is 2940 veh/hr. To be more precise we look at the ratio of throughput over demand. The average ratio under the dynamic early merge was the highest of 0.8734 followed by the dynamic late merge of 0.855 then followed by the MAS of 0.839. This fact means that the early merge has the highest throughput given the demand volumes. Looking at Table 5.4 we can notice that the mean percent car lane changing in zone one is the highest for the dynamic early merge and the lowest for the dynamic late merge. Also looking at the percent truck lane changing in zone 1, the highest mean percent lane changes is for the dynamic early merge and the lowest is for the dynamic late merge. This means that some drivers are obeying the message displayed by the dynamic message boards.

Table 5.4: Descriptive Statistics

Descriptive statistics						
		Unit	**Minimum**	**Maximum**	**Mean**	**Std. Deviation**
MAS	Demand Volume	Veh/hr	0	2580	911.92	467.4
	Throughput	Veh/hr	270	2730	1064.87	488.58
	Truck %	N/A	0	0.5	11.3	0.1078
	% Car Lane Change Z1	N/A	0	1	52.08	0.2839
	% TRK Lane Change Z1	N/A	0	1	60.68	0.4159
	Ratio (Throughput/Demand)	N/A	0	1	0.839	0.202
Early Merge	Demand Volume	Veh/hr	120	1530	713.17	406.63
	Throughput	Veh/hr	0	1890	763.96	377.49
	Truck %	N/A	0	0.74	17.84	0.1909
	% Car Lane Change Z1	N/A	0	1	59.55	0.3098
	% TRK Lane Change Z1	N/A	0	1	66.34	0.3543
	Ratio (Throughput/Demand)	N/A	0	1	0.8734	0.2071
Late Merge	Demand Volume	Veh/hr	180	3120	1209.06	577.11
	Throughput	Veh/hr	60	2940	1152.81	596.01
	Truck %	N/A	0	0.54	13.84	0.1129
	% Car Lane Change Z1	N/A	0	1	46.35	0.3424
	% TRK Lane Change Z1	N/A	0	1	18.06	0.3738
	Ratio (Throughput/Demand)	N/A	0.15	1	0.855	0.1766

Table 5.5: Regression Analysis Results

ANOVA AND PARAMETER ESTIMATES				
Parameter	**Estimate**	**Standard Error**	**t Value**	**Pr > |t|**
Intercept	0.6429	0.0318	20.2300	<.0001
% Trucks	-0.1264	0.0840	-1.5000	0.1330
% PC Lane Changing in Zone 1	0.1246	0.0349	3.5700	0.0004
%TRK Lane Changing in Zone 1	0.1256	0.0277	4.5400	<.0001
Dynamic Late Merge	0.0710	0.0265	2.6800	0.0077
Dynamic Early Merge	0.0956	0.0298	3.2100	0.0014
MAS	0	.	.	
OVERALL ANOVA				
Source	**Sum of Squares**	**Mean Square**	**F Value**	**Pr > F**
Model	3.369	0.674	11.520	<.0001
Error	29.879	0.058		
Corrected Total	33.248			

For a better understanding of the variables affecting the ratio and multiple linear regression analysis was conducted (See Table 5.5). Recall that the ratio is the throughout volume over the demand volume. The ratio could take a maximum value of 1 meaning that all demand volume is processed and a minimum of 0 meaning that none of the incoming vehicles (demand volume) exited the work zone.

The P-value (last column) in Table 5.5 having a value <0.05 means that this variable affects the ratio significantly. A positive parameter estimate (first column) means that the effect on ratio is positive and a negative value means that the effect is negative. The significant variables affecting the ratio are highlighted in the last column. From the above model, it is shown the higher the passenger car and truck lane changes in zone 1 the higher the ratio (meaning a better processing for the work zone). The model also shows that the dynamic early merge and the dynamic late merge compared to the MAS (base case, always takes value of zero), have a positive effect on ratio. This means that the dynamic early merge and the dynamic late merge enhance the throughput of the work zone. Notice that the parameter of the dynamic early merge is higher than the parameter of the dynamic late merge. This means that compared to the MAS, dynamic early merge is slightly better than the dynamic late merge. The above analysis studies the overall effect of the variables on ratio. This section discriminates between demand volumes. Five volume groups were created: V1 between 0-500 veh/hr, V2 between 501-1000veh/hr, V3 between 1001-1500veh/hr, V4 between 1501-2000 veh/hr, and V5 >2000 veh/hr.

Five regression models were conducted for each volume group and the results are shown in Table 5.7. Table 5.6 summarizes the results from the regression analyses. The red color means lower ratio than MAS, the color yellow means higher but not significant, the color green means higher and significant, the blue color means unknown. To compare dynamic early and late merge we used the letters E and L. As shown by the Table 5.6, the late SDLMS was better than the early SDLMS for V4.

Table 5.6: Comparison of Early SDLMS, Late SDLMS and MAS for Volumes

Late and Early Compared to MAS					
	V1	**V2**	**V3**	**V4**	**V5**
Dynamic Early Merge					
Dynamic Late Merge				L	

Table 5.7: Five Regression Models' Results for Each Volume

0-500 veh/hr

ANOVA AND PARAMETER ESTIMATES

Parameter	Estimate	Standard Error	Pr > |t|
Intercept	0.880	0.083	<.0001
% Trucks	-0.088	0.149	0.558
% PC Lane Changing in Zone 1	-0.008	0.089	0.925
%TRK Lane Changing in Zone 1	0.032	0.070	0.653
Dynamic Late Merge	-0.234	0.083	0.006
Dynamic Early Merge	0.058	0.055	0.291
MAS	0	.	.

501-1000 veh/hr

ANOVA AND PARAMETER ESTIMATES

Parameter	Estimate	Standard Error	Pr > |t|
Intercept	0.627	0.056	<.0001
% Trucks	-0.222	0.161	0.170
% PC Lane Changing in Zone 1	0.071	0.064	0.269
%TRK Lane Changing in Zone 1	0.187	0.048	0.000
Dynamic Late Merge	0.082	0.050	0.102
Dynamic Early Merge	0.133	0.054	0.014
MAS	0	.	.

1001-1500 veh/hr

ANOVA AND PARAMETER ESTIMATES

Parameter	Estimate	Standard Error	Pr > |t|
Intercept	0.652	0.054	<.0001
% Trucks	-0.288	0.168	0.090
% PC Lane Changing in Zone 1	0.141	0.067	0.038
%TRK Lane Changing in Zone 1	0.104	0.044	0.018
Dynamic Late Merge	0.099	0.042	0.187
Dynamic Early Merge	0.029	0.053	0.059
MAS	0.000	.	.

1501-2000 veh/hr

ANOVA AND PARAMETER ESTIMATES

Parameter	Estimate	Standard Error	Pr > |t|
Intercept	0.523	0.074	<.0001
% Trucks	0.004	0.292	0.988
% PC Lane Changing in Zone 1	0.166	0.081	0.044
%TRK Lane Changing in Zone 1	0.122	0.072	0.097
Dynamic Late Merge	0.204	0.063	0.002
Dynamic Early Merge	0.156	0.152	0.031
MAS	0.000	.	.

>2000 veh/hr

ANOVA AND PARAMETER ESTIMATES

Parameter	Estimate	Standard Error	Pr > |t|
Intercept	0.760	0.176	0.001
% Trucks	-3.068	1.020	0.010
% PC Lane Changing in Zone 1	0.043	0.152	0.782
%TRK Lane Changing in Zone 1	0.569	0.315	0.094
Dynamic Late Merge	0.203	0.176	0.271
Dynamic Early Merge	0.000	.	.
MAS	0.000	.	.

6. ESTIMATED EQUIPMENT COSTS

The budgetary quotations from IRD Inc. for a standard Lane Merger System with one Portable Changeable Message Trailer (to be provided by the state or others) and one Sensor Trailer, complete with a Central Controller and Software License are shown below. Installation including training is provided with the initial deployment. The first quotation is for using the RTMS to operate the system and the second quotation is for using the speed radar to operate the system. It should be noted that the speed radar system should be used when the speed is the only factor to trigger the system and it covers only two to three lanes.

INTERNATIONAL ROAD DYNAMICS INC.
INTELLIGENT TRANSPORTATION SYSTEMS

TO:	University of Central Florida
FROM:	International Road Dynamics Inc.
PROJECT:	ITS Dynamic Lane Merge System
DATE:	March 20, 2009

PRICE QUOTATION

System Type:	Lane Merger.
System Components:	2 roadside remote instrumentation, 1 Central Controller, 1 Software License IRD to supply 1 sensor trailer (PCMS to be supplied by University or State)
Duration of Rental:	12 months rental
Mobilization:	System delivery to state specified location, installation assistance, and initial training included.
Support:	Warranty parts replacement for one year. Additional offsite troubleshooting and support package for one year can be offered at $3,125. Additional onsite support can be provided for an additional $1,995 per day which includes travel to and per diems.
Insurance coverage:	Equipment insurance provided by IRD during rental. Client responsible following purchase.

<u>FDOT / University of Central Florida Responsibilities</u>

Traffic control:	Traffic control during setup, mobilization, and take down responsibility of FDOT.
Traffic protection:	Cones/barrels/ barricades as required to be supplied and maintained by FDOT for each trailer.
Relocation:	Additional relocation or movement of trailers after initial mobilization will be FDOT's responsibility and is not included in the rental or purchase price.
Staging:	We would expect the state or its contractor to provide a staging area for the PCMS and sensor trailer and to transport those items to and from the field site.
Monitoring:	FDOT responsible for visual driveby check of system.
Customer supplied	FDOT to supply PCMS. equipment

ITEM:	PRICE:
RENTAL	
EQUIPMENT RENTAL, INSTALLATION AND TRAINING FOR INITIAL DEPLOYMENT (1year rental Term)	$42,990
PURCHASE	
EQUIPMENT PURCHASE, INSTALLATION AND TRAINING FOR INITIAL DEPLOYMENT	$58,620

TERMS AND CONDITIONS:

- Prices are in U.S. Dollars.
- Prices are FOB Florida.
- Prices do not include Federal, State or local taxes (if applicable).
- Prices are budgetary and may be subject to change.
- Payment terms are net 30 days OAC.

702 43rd Street East, Saskatoon, Saskatchewan CANADA S7K 3T9 Telephone: (306) 6536600 Facsimile: (306) 2425599
US IRD Corp: Spring Grove, Illinois Telephone: 18774444IRD (4473) Facsimile: (306) 2425599
www.irdinc.com

INTERNATIONAL ROAD DYNAMICS INC.
INTELLIGENT TRANSPORTATION SYSTEMS

TO:	University of Central Florida
FROM:	International Road Dynamics Inc.
PROJECT:	ITS Dynamic Lane Merge System (Without RTMS Microwave Radar)
DATE:	March 20, 2009

PRICE QUOTATION

System Type:	Lane Merger.
System Components:	2 roadside remote instrumentation with speed radar only, 1 Central Controller, 1 Software License IRD to supply 1 sensor trailer (PCMS to be supplied by University or State)
Duration of Rental:	12 months rental
Mobilization:	System delivery to state specified location, installation assistance, and initial training included.
Support:	Warranty parts replacement for one year. Additional offsite troubleshooting and support package for one year can be offered at $3,125. Additional onsite support can be provided for an additional $1,995 per day which includes travel to and per diems.
Insurance coverage:	Equipment insurance provided by IRD during rental. Client responsible following purchase.

FDOT / University of Central Florida Responsibilities

Traffic control:	Traffic control during setup, mobilization, and take down responsibility of FDOT.
Traffic protection:	Cones/barrels/ barricades as required to be supplied and maintained by FDOT for each trailer.
Relocation:	Additional relocation or movement of trailers after initial mobilization will be FDOT's responsibility and is not included in the rental or purchase price.
Staging:	We would expect the state or its contractor to provide a staging area for the PCMS and sensor trailer and to transport those items to and from the field site.
Monitoring:	FDOT responsible for visual driveby check of system.
Customer supplied	FDOT to supply PCMS. equipment

ITEM:	PRICE:
RENTAL	
EQUIPMENT RENTAL, INSTALLATION AND TRAINING FOR INITIAL DEPLOYMENT (1year rental Term)	$40,475
PURCHASE	
EQUIPMENT PURCHASE, INSTALLATION AND TRAINING FOR INITIAL DEPLOYMENT	$50,250

TERMS AND CONDITIONS:

- Prices are in U.S. Dollars.
- Prices are FOB Florida.
- Prices do not include Federal, State or local taxes (if applicable).
- Prices are budgetary and may be subject to change.
- Payment terms are net 30 days OAC.

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7. DISCUSSIONS AND CONCLUSIONS

This study suggested two Simplified Dynamic Lane Merging Systems (SDLMS) for deployment and testing on short term work zones. The first SDLMS is a simplified dynamic early merge system (early SDLMS) and the second SDLMS is a simplified dynamic late merge system (late SDLMS). The UCF research team coordinated the project with multiple entities including FDOT, consultant, vendors, etc. Two sites were selected for data collection and analysis. The first site was located on I-95 in Malabar, Florida consisting of a two to one lane closure. The second site was located on I-95 in Palm Beach, Florida consisting of a three to two lane closure.

Looking at the first site, the capacity of the work zone under the control (MAS) and test MOT plans (early and late SDLMS) were compared. A regression model showed that the early SDLMS enhances work zone capacity significantly from 881 veh/hr to 970veh/hr. The late form of SDLMS increased the mean capacity from 881 veh/hr to 896 veh/hr, however this increase was not statistically significant. The travel time through the work zone under the control and test MOT plans were also examined. The average travel time for the MAS, early and late SDMLS were 3.97minutes, 3.87 minutes, and 3.78 minutes and a statistical test showed that the means were not statistically significant. This indicates that the simplified dynamic early and late merge did not affect the travel time through the work zone. The number and percentage of lane changes in zone 1 were the highest for the early SDLMS and the lowest for the late SDLMS. This indicates that drivers were complying to some extent with the messages displayed by the additional PCMS. It was noticed during data collection, for the early SDLMS, that drivers usually comply with the messages displayed by the PCMS. However, it was also observed that when a vehicle uses the closed lane to pass vehicles in the queue and merge into the open lane ahead of them, a platoon of vehicles follows this vehicle which defeats the purpose of the early SDLMS. From the first site, it is suggested that the dynamic early merge performs better than the MAS system.

Data was collected extensively on the second site which enabled us to compare safety and operational MOEs under different demand volumes. The temporal speed fluctuation at the location of the RTMS of the work zone under the control (MAS) and test MOT plans (early and late SDLMS) were compared. The mean speed fluctuation in the closed lane was the highest under the MAS system for all demand volumes. The dynamic late merge and the dynamic early merge have lower speed fluctuations in the closed lane under all demand volumes compared to the MAS system. Comparing the dynamic early merge and the dynamic late merge mean speed fluctuations in the closed lane, results showed that the mean speed fluctuation for the early merge are lower than those of the late merge under demand all demand volumes. However, the difference in the mean speed fluctuation is only statistically significant under demand volume ranging between 0 and 500 veh/hr. Results showed that the speed fluctuations in the middle lane are the highest for the MAS system compared to dynamic early merge and dynamic late merge under all demand volumes. However, results showed that the mean speed fluctuations under the MAS are significantly higher than the mean speed fluctuations under the dynamic late merge only for volumes for volumes greater than 1500 veh/hr (and marginally at volumes between 1000 and 1500 veh/hr). The mean speed fluctuations under the MAS are significantly higher than the mean speed fluctuations under the dynamic early merge system for volumes ranging between 500 and 1500 veh/hr. Comparing the mean speed fluctuations under the dynamic early merge and the dynamic late merge, it was found that the mean speed fluctuations are lower for the dynamic early merge. However, there was no significant difference between the speed fluctuations in the middle lane.

Looking at the speed fluctuations in the shoulder lane, the mean speed fluctuations are the highest under the MAS system compared to the dynamic early merge and the dynamic late merge under all volumes. The mean speed fluctuations for the MAS system is significantly higher than the mean speed fluctuation for dynamic early and dynamic late merge for volumes under 1000 veh/hr. Moreover, there exist a marginal significance indicating that the mean speed fluctuation for the late merge is lower than the mean speed fluctuation for the MAS system for volumes ranging 1000 veh/hr to 2000 veh/hr. Comparing the mean speed fluctuations between the dynamic early and dynamic late merge, it was noted that the means speed fluctuations are lower for the dynamic late merge under volumes higher than 500 veh/hr. However, it was shown that the mean speed fluctuation for the dynamic late merge is significantly lower than the mean speed fluctuation for the dynamic early merge for demand volumes ranging between 1500 veh/hr and 2000 veh/hr.

The ratio of the throughput over demand volume was taken as the operational MOE. Results showed that the Dynamic early merge performs significantly better than the regular MAS under demand volume ranging between 500 veh/hr and 2000 veh/hr. Results also showed that the dynamic late merge perform better than the MAS under volumes ranging between 1500 veh/hr and 2000 veh/hr and significantly poorer than the MAS under low volumes. Therefore, the late SDLMS is not recommended for implementation under low volumes. Results also showed that the late SDLMS performs better than the early SDLMS under higher volume (ranging between 1500 veh/hr to 2000 veh/hr).

Combining safety and operational measures discussed above, some recommendations can be drawn regarding the implementation of the early SDLMS and late SDLMS:

- For volumes ranging between 0 and 500 veh/hr, it was found that the dynamic early merge performs better than the dynamic late merge and MAS. The dynamic late merge shows the poorest performance under this range of volume.

- For volumes ranging between 501 veh/hr and 1000 veh/hr the dynamic early merge exhibits the best performance compared to the dynamic late merge and the MAS system.

- For volumes ranging between 1001 veh/hr and 1500 veh/hr the dynamic late merge exhibits the highest performance compared to the dynamic early merge and the MAS system.
- For volumes larger than 1501 veh/hr and 2000 veh/hr, dynamic early merging data was not available. However, the dynamic late merging showed better performance than the MAS system.

This study showed that the early and late SDLMS have the potential to enhance safety as well as operations in Florida work zones. It is recommended that further analyses that would entail all possible traffic and geometric characteristics be conducted using simulation. Data from this study can be used to calibrate and validate the simulation and multiple scenarios can be designed in the simulation model.

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