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16. Abstract

Practices for the design and control of work zone traffic control configurations have evolved over time to reflect safer and more efficient management practices. However, they are also recognized as areas of frequent vehicle conflicts that can cause congestion and safety problems. In this research, a new design has been developed that could lessen some of these detrimental effects. This new concept, known as the "joint merge," simultaneously merges two lanes into one. The key feature of the design is its two-sided taper in which the two adjacent lanes approaching a lane reduction are simultaneously tapered into a single lane with neither lane having a priority. This is theorized to influence drivers into merging in a smooth alternating pattern. To evaluate its operational effects, the joint merge was examined in a work zone in Louisiana and compared to an MUTCD conventional merge configuration at the same site. Lane-specific volume and vehicle speeds were collected in the field and the two designs were compared using Analysis of Variance (ANOVA) and T-test statistical procedures. Overall, the joint merge was found to increase the efficiency of the closed lane and encourage the use of both lanes into the work zone entrance. It was also found that the number of lane changes during low and high-volume periods decreased when the joint merge configuration was used. While no conclusive findings could be made relative to its specific effect on capacity, video recordings and lane usage data suggested that the joint merge strategy was understood and well received by most drivers.

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October 2012

ABSTRACT

The design and control of work zone traffic control areas is governed by standards published by the United States Department of Transportation (US-DOT) and documented in the Manual for Uniform Control Devices (MUTCD). While these configurations have evolved over time to reflect safer and more efficient management practices and have become familiar to drivers, they are also recognized as areas of vehicle conflict that can cause congestion and safety problems.

In this research, a new design was developed to potentially reduce the detrimental effects of lane closures in work zones. This new concept, known as the "joint merge," is configured to simultaneously merge two lanes into one. The key feature of the joint merge design is its use of a two-sided taper. In it, both lanes approaching a lane reduction are simultaneously tapered into a single lane, with neither lane having a priority, thereby influencing drivers to merge in a smooth alternating pattern.

The joint merge configuration was tested in freeway work zone sites in Louisiana and its performance compared to that of a conventional MUTCD merge configuration erected at the same site. The performance measures collected in the field included lane-specific volume and vehicle speeds. The two designs were quantitatively compared using Analysis of Variance (ANOVA) and T-test statistical procedures. These two testing agents were used to analyze the effects each design had on volume, speed, and vehicle lane distributions at several locations in advance of the work zone entrance.

Using speed and volume data, the joint merge traffic control plan was found to increase the efficiency of the closed lane and better encourage the use of both lanes leading up to the work zone entrance. It was also concluded that the number of lane changes during low and high-volume periods decreased when the joint merge configuration was used. While no conclusive findings could be made relative to its specific effect on capacity, video recordings and lane usage data suggested that the joint merge strategy was understood and well received by most drivers.

ACKNOWLEDGMENTS

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IMPLEMENTATION STATEMENT

While it is not possible to confidently conclude that the joint merge strategy was more beneficial than other unconventional strategies, there were subtle differences between the two configurations in this study that suggest, if applied under the right circumstances, the joint merge may outperform others. For instance, on-ramps near a transition zone entrance is problematic for the conventional and early merge configurations since motorists position themselves for a right or left merge are in conflict with vehicles merging from the on-ramps. Lane priority is not established for the joint merge configuration and therefore the potential conflict with vehicles merging from the on ramp is minimized. The joint merge may also be applied in anticipation of large volumes of traffic where full utilization of both lanes leading into the work zone is desired. Pesti et al. (1999) reported increases in the percentage of vehicles using the closed lane when implementing the late merge strategy, but also concluded that the overall benefit of the late merge remains to be seen since motorists tended not to stay in the closed lane until the merge point as instructed. This non compliancy has been thought to be attributed to the physical layout of the traffic control devices used in the late merge strategy. By contrast, the joint merge configuration developed here encouraged drivers to use both lanes until reaching the transition entrance.

Although the dynamic late merge strategy was suggested in some studies to function effectively in both low and high-volume traffic streams, the set up and maintenance cost in comparison to the joint merge is substantial. The dynamic late merge encompasses vehicle sensors that activate and deactivate beacon lights. The lights are attached to signs that inform drivers when to switch from the late merge strategy to the conventional merge strategy. This change can be very abrupt during high-volume periods and is dependent on technology that has at times failed, raising some safety concerns. Although this is the first study of its kind, the joint merge has also shown the potential to be effective at low and high-volumes by better maintaining speeds in the closed lane and creating a more equal distribution of vehicles by lane. Additionally, the joint merge has less set up and maintenance costs than the dynamic late merge even though it requires twice as many arrow boards and channeling devices. This suggests that the joint merge strategy can be a cost-effective alternative while achieving similar levels of benefit.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

INTRODUCTION

With more than 3,000 highway construction work zones in operation on the national highway system on any given day, there is an increasing need to provide safe and efficient mobility for vehicles traveling in the vicinity of the work zones (U.S. Department of Transportation, 2002). It has been estimated that the typical motorist encounters an active work zone almost every 100 miles (Ullman, 2004). Therefore, driving past or near a construction zone has become a common occurrence for most drivers. However, fatalities from motor vehicle crashes in work zones increased approximately 50 percent between 1997 and 2003 (U.S. Department of Transportation, 2003). More specifically, 1,028 fatalities occurred in work zone related crashes, with an additional 40,000 injuries in 2003 (National Cooperative Highway Research Program, 2005).

The increase in driver risk created by work zones are often attributed to roadway maintenance work, which often requires the closing of at least one lane during construction periods. Construction periods range from hours to years depending on the type of work being done and the specific conditions that exist at the site (i.e., roadway type, roadway volume, posted speed limit, roadway configuration). There are three types of construction periods: short, intermediate, and long term. Short-term construction is typically accomplished during the day and lasts from 1-12 hours. Intermediate construction may be performed overnight but lasts no more than three days. Any work anticipated to require more than three days of construction is classified as long-term work. Regardless of the work classification, construction in work zones requires the closure of at least one lane and often results in decreased capacity, an increase of hazards, and longer delays for drivers.

An important feature of the work zone configuration is the transition zone. In transition zones, available lanes gradually decrease and arriving traffic moves out of the lane closed for construction. Since lane closures reduce capacity, areas before the transition zone can become highly congested during heavy traffic periods with queues stretching for miles ahead of the transition zone. Another problem associated with transitions in work zones is driver dissatisfaction and frustration. A recent study found that a third of drivers were dissatisfied with work zones on highways (U.S. Department of Transportation, 2001). In addition to safety concerns, motorist dissatisfaction may be influenced by reduced capacity and increased travel time.

Kim, Wang, and Ulfarsson (2007) reported approximately 60 percent of freeway congestion is caused by “expected incidents” such as work zones or “unexpected events” such as crashes. Work zone lane closures have been shown to increase congestion during heavy volume periods. In low to medium volume conditions, transition zones function with few problems since there are numerous gaps of adequate size for drivers to change lanes. Drivers in open lanes often adjust their speed to create gap opportunities for merging drivers, similar to freeway on-ramp situations. However, once traffic demand reaches or exceeds capacity in transition areas, speeds rapidly drop and queues of slower-moving traffic begin to form. During high-volume periods, these queues can extend upstream for long distances, intensifying driver frustration as conflicts arise between vehicles approaching the transition zone.

Three lanes are involved in guiding vehicles through transition zones. Throughout this study, those lanes are referred to as “closed,” “open,” and “merged” lanes and are shown in Figure 1. Open lanes are unaltered lanes for which vehicles traveling in them are not shifted laterally. Closed lanes terminate, and vehicles in them are required to transition to the adjacent right or left lane depending on the configuration. Merged lanes are lanes downstream of the transition zone that carries traffic from both of the entry lanes. They are located immediately after the taper and receive traffic from both closed and open lanes. A taper restricts the longitudinal movement and is used to channel vehicles into the merged lane.

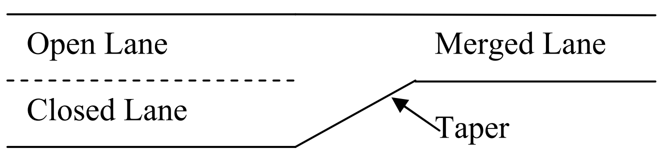


Figure 1
Lanes involved in merging maneuvers

Most lane closures result in vehicles in the closed lane merging with vehicles in an adjacent open lane. Familiar drivers often position themselves in the open lane prior to the upcoming lane closure. It is more common for unfamiliar and aggressive drivers to be positioned in the closed lane. Louisiana traffic law, similar to that in other states, requires merging vehicles to yield to vehicles in the open lane to which right of way (ROW) has been assigned (Louisiana Department of Public Safety and Corrections, 2009). A traffic control device such as the W4-2 sign shown in Figure 2 is used to warn approaching vehicles that a certain merging maneuver is required.

Figure 2
Illustrated warning signs
(source: MUTCD 2003)

Standard design practices for the design of lane closures in work zones are published in the Manual on Uniform Traffic Control Devices (MUTCD). It states that work zones should maintain driver familiarity. To do so, lane closures are designed so that drivers travel safely through the Temporary Traffic Control (TTC) zone, reducing speeds no more than 10 mph. Other research showed accident rates and speed variances were lowest when these types of speed limit reductions were maintained (Migletz, Graham, Anderson, Hardwoon, & Bauer, 1999). The MUTCD (2003) also suggests the application of the following equations to calculate the minimum required length of the transition zone.

For speeds equal to or greater than 45 mph

$$L = WS \qquad (1)$$

And for speeds equal to or less than 40 mph

$$L = \frac{WS^2}{60} \qquad (2)$$

where,
W= the width of the lane (ft.);
S= the posted speed, 85 percentile speed, or the calculated speed (mph); and
L= the longitudinal length of the transition area (ft.)

For a closure of a single 12-ft. lane with a posted speed limit of 45 mph, the minimum transition taper length would be 12 ft. x 45 mph = 540 ft. A standard MUTCD design for temporary traffic control during closures of four-lane divided highways is shown in Figure 3.

This design has been developed over many years of study and application to maximize the safety and efficiency of traffic operations. Also illustrated in Figure 3 is the typical signage involved in a lane closure. These signs are placed at various locations in the advance warning area, which is an area designated for the purpose of warning motorists of an upcoming work zone and a possible lane closure. The values of A, B, and C shown in Table 1 are the recommended placements of advance warning signs for use in work zones and incident areas. Where in feet: A is the distance from the start of the taper to the first sign, B is the distance from the first sign to the second sign and, C is the distance from the second sign to the third sign.

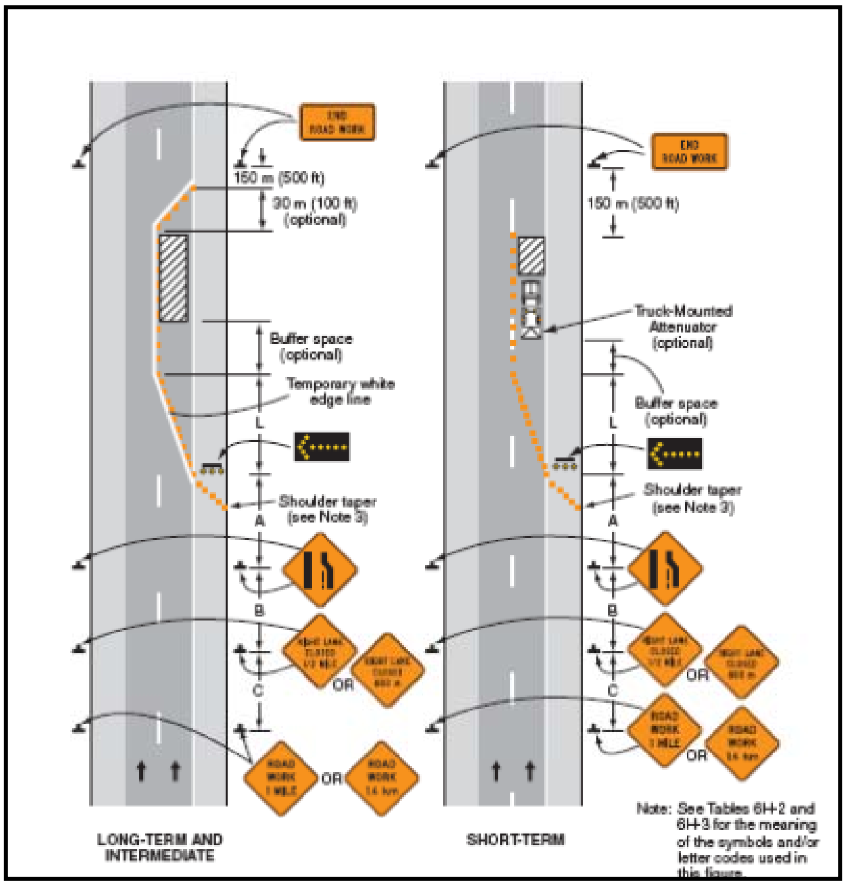


Figure 3
MUTCD typical applications of a "stationary lane closure on divided highways"
(source: MUTCD, 2003)

Table 1
Advanced warning sign measurements (source: MUTCD, 2003)

Road Type	A	B	C
Urban (low speed)	100’	100’	100’
Urban (high speed)	350’	350’	350’
Rural	500’	500’	500’
Expressway/ Freeway	1,000	1,500	2,640’

A central aspect of traffic operations within these areas is the established flow hierarchy in which motorists in the open lane have right-of-way and drivers in the closed lane must adjust their speed to merge into a gap in the open lane. Polus and Shwartzman (1999) concluded that throughput in work zones are mainly dependent on the geometry, location, and traffic control plan of the work zone.

OBJECTIVE

The goals of this research were to develop and test alternative strategies of traffic control that could enhance the safety and efficiency of merging operations within lane-drop merge areas. The current lane closure design specified in the MUTCD seeks to guide drivers from the closed lane to the merged lane. It has been theorized, however, that such maneuvers can be unsafe and inefficient during high-volume periods. A high concentration of vehicles in the open lane creates an imbalance in lane volume, which can lead to longer queue lengths and different operating speeds between the open and closed lanes. Differential speeds have been recognized to be related to increased crash frequency (National Cooperative Highway Research Program, 2007).

From a driver behavioral standpoint, some aggressive drivers take advantage of the imbalanced conditions to pass slower-moving or stopped traffic for as long as possible; even proceeding to the very front of the queue before merging into the open lane. This creates irritation among drivers who merge early and have "waited their turn" instead of moving to the very front of the queue and merging into an insufficient gap. On occasion, some drivers have combated these conditions by resorting to partially or even fully blocking the closed lane to prevent late merging drivers from passing. Similar behaviors are also exhibited by truck drivers who create "rolling blockades" by driving side by side at the same speed and prevent vehicles from passing (Pesti, Jessen, Byrd, and McCoy, 1999). In the past, these conditions have even led to dangerous maneuvers like driving on shoulders, incidents of road rage, and in some locations, even fatal traffic crashes (Massachusetts Highway Department, 2006).

A review of literature revealed that a considerable amount of research on improving the safety and mobility of vehicles in work zones has been conducted (U.S. Department of Transportation, 2002). However, improving the transition zone's geometric layout has not been considered as a possible solution to the ongoing merging problem at the entrance of the transition zones. Enhancing geometric design features such as taper lengths and alignment of channeling devices, in addition to, experimental signs and/or other traffic control measures may lead to more positive results.

Tasks

To accomplish the research goals, a series of work tasks were undertaken. These tasks are listed next in the order in which they were carried out. The following chapters of this report detail the activities associated with these tasks as well as the results that were gained from them.

1. Identify and document both the state-of-the-art and state-of-the-practice on activities in the geometric design and traffic control at the entrance to construction work zones on rural freeways.

2. Select or design a merging strategy that was thought to accomplish a more efficient merge than current designs.

3. Identify potential sites on rural freeways in Louisiana to test and compare the conventional and experimental merge configuration.

4. Generate alternative traffic control schemes for the selected experimental merge design, and apply them to the appointed work zone test site.

5. Obtain lane specific speed and volume data from the work zone site.

6. Evaluate and analyze the traffic data gathered for the two design configurations, the experimental, and the conventionally used configuration

7. Document results.

8. Provide recommendations on design features that are thought to enhance the function of the experimental merge configuration.

SCOPE

This study involved a comparative test of the joint merge and conventional MUTCD merge designs for temporary freeway lane drop merge areas associated with construction work zones. To conduct the comparison on a quantitative basis, field data were collected over a short segment of the northbound lanes of Interstate 55 freeway in the vicinity of Hammond, Louisiana. Although this area was near Hammond, the general design, volume, and vehicle operating characteristics would generally suggest "rural" freeway conditions.

Vehicle speeds and lane presence (volume/flow) were collected using Vehicle Magnetic Imaging Recorders (VMIR) affixed to the pavement at nine separate locations at key points entering into the merge zone and immediately downstream where traffic occupied a single-lane. Within this arrangement traffic operating conditions could be evaluated temporally and spatially as well as by specific lane. In total, over 600 hours of data were collected for both configurations. Since the data collectors recorded continuously, it was possible to acquire data over a variety of traffic volume and environmental conditions. This would include a period of high, medium, and low traffic volume as well as a mix of weather and daylight conditions.

In addition, the project also included the purchase, set up, and testing of all equipment that was used to collect the field data as well as the techniques of data reduction and analyses that would be used to comparatively evaluate the results. These methodologies and systems are assumed to be easily transferable to other locations and roadway types to conduct similar studies in other areas.

METHODOLOGY

This research study sought to identify and examine a merging strategy thought to be best suited for lane closures in work zones. Findings from literature suggested a “zipping” merge configuration that effectively influenced an alternating merge pattern would be more beneficial than current merging strategies. Although past attempts to influence an alternating merge pattern at the transition zone entrance were made, documented procedures on using channeling devices to encourage an alternating merge were not found to exist. Channeling devices are a key component in the design of a merge configuration since they operate as a guide for traffic merging into a neighboring lane.

An experimental merge configuration was examined at a work zone site in Louisiana and compared to the conventional configuration specified in the MUTCD. Several steps were involved in the design and testing of the experimental merge referred hereon as the joint merge. Those steps are explained in progressive order in this chapter.

The motivation for selecting the joint merge as the merge configuration to test is explained first. Next the process of designing the joint merge configuration to be incorporated in a work zone traffic control plan is discussed. Criteria used in the selection of a test-worthy site follow. The remaining sections in the chapter are used to describe the placement and capabilities of the equipment used in recording data and the measures of effectiveness used to compare the two configurations.

Experimental Merge Design Selection

Joint Merge Concept

After an assessment of the advantages and disadvantages of each work zone merging strategy, it was determined the most beneficial strategy would be one that is cost efficient, intuitive to motorists and relatively easy to implement. Three of the seven merging strategies highlighted in the literature review were found to have at least one of these benefits. The late merge, in some studies, was reported to decrease queues and increase flow due to both lanes being utilized up to a certain location. The “always close right lane” strategy was thought to decrease driver confusion on which lane is closed. Lastly, the zipping concept was used in the Connecticut Department of Transportation (CDOT) Alternating Merge study and was reported to decrease the number of “undesirable” merges and increase “desirable” ones. The joint merge encompasses all of the ideal attributes by encouraging the use of both lanes, decreasing confusion on which lane is closed, and by creating a cooperative environment where motorist share the responsibility of merging. Based on these anticipated outcomes, the joint merge was hypothesized to increase the mobility and safety of traffic passing through a work zone.

The joint merge is a traffic control plan for use in temporary and long-term work zones. It makes use of signage in the advance warning area and channeling devices in the transition zone to create an evenly balanced distribution of vehicles in each lane. Using a series of warning signs and a "funnel-shaped" arrangement with traffic control devices at the entrance of the transition zone, the joint merge simultaneously merges two lanes into one.

Selection of a Joint Merge Traffic Control Layout

Three alternative joint merge design schemes were presented to a committee comprised of state and local traffic officials and researchers. Of the three alternative design schemes, one was selected for testing at a work zone site. The alternative merge designs were similar in every way except for the design of the transition zone and the placement of the signs. The sign used in alternative one was a single overhead flashing arrow board that spanned across the lanes and showed two arrows converging. The transition zone was divided into two segments; the first simultaneously transitioned two lanes into one and the second shifted vehicles to the left away from construction.

The W4-2 sign shown in Figure 4 was used in the second alternative joint design scheme. To communicate the convergence of two adjacent lanes, different versions of the W4-2 signs were placed on the right and left sides of the roadway where the symbolic W4-2 Merge Right sign was placed on the right side of the road and the W4-2 Merge Left sign was place on the left. Similar to alternative one, the transition zone was divided into two segments. The first segment tapered two lanes into one and the second shifted vehicles to the left away from construction.

Combining design elements of one alternative scheme with another, such as using the overheard panel in scheme one with the geometric layout of scheme two, was also explored. Ultimately the third alternative design scheme possessed all of the necessary components to produce an effective joint merge, and was used for the study. Full descriptions of the joint merge design components follow.

Joint Merge Design Components

The traffic control plan of the joint merge configuration along with its conventional traffic configuration counterpart is shown in Figures 4 and 5. Although the joint merge design is similar to the late merge and zipper merge concept, it differs in a very distinct way. That is, the joint merge incorporates channeling mechanisms that physically and progressively constrain the position of vehicles on the roadway leading them to combine more naturally; whereas, the late and zipper merge concepts are essentially "rules of the road." Moreover, there have been findings that suggest the late merge rules are not consistently followed by drivers, often due to confusion and unfamiliarity with the concept. This is thought to be attributed to the physical configuration of the traffic control devices.

Transition Zone

The joint merge configuration's transition zone was divided into three segments. Segments one, two, and three are shown in Figure 6 colored purple. The first segment gradually merged the two arriving traffic streams into one, the second segment was used to create a sense of being in one lane before reaching the third segment, which redirected the vehicles to the left or right. The distances of each segment are L, ½ L, and ½ L, respectively, where L, shown in Equation (1), is the length of the taper and is calculated by using the width of the lane and the pre-work zone posted speed limit. The MUTCD recommends the length of shifting tapers, such as the one used in segment three, be at least half the distance of the merging taper length in segment one. The redirection of vehicles in the third segment is governed by the location of construction. In this study, right lane closures were performed therefore, the third segment was used to channel vehicles to the left lane as shown in Figure 7.

Traffic Control Devices

Signs. Three experimental signs were included in the joint merge design. Two textural signs, "Lane Closed Ahead" and "Both Lanes Merge" along with the symbolic joint merge sign designed by CDOT were used to communicate the required merging movements to motorists. The symbolic joint merge sign in Figure 2 was one of many involved in a survey conducted by CDOT and with permission was the sign of use in this project.

Arrow Boards. In addition to the static signs, two arrow boards were positioned on both sides of the transition zone entrance. This arrangement alerted motorists of transition from two lanes to one.

Channeling Devices. Following the arrow boards were channeling devices spaced at 40 ft. intervals in the direction of travel. The lateral distance between the channeling devices decreases gradually to 16 ft. The decrease in lateral distancing began at the entrance of the transition zone and extended to the end of the first transition zone segment. Louisiana state law requires that channeling devices used in work zones lasting longer than a half day be equipped with beacon lights that are set to operate during evening hours. In this study beacon lights were attached to each channeling device.

Changeable Message Boards. Changeable message boards (CMB) are mobile message units that display transcribed information and inform drivers of conditions that require extra attention. When used properly, they are more effective than static signing. An effective CMB is able to convey a message in an understandable manner and in a short amount of time.

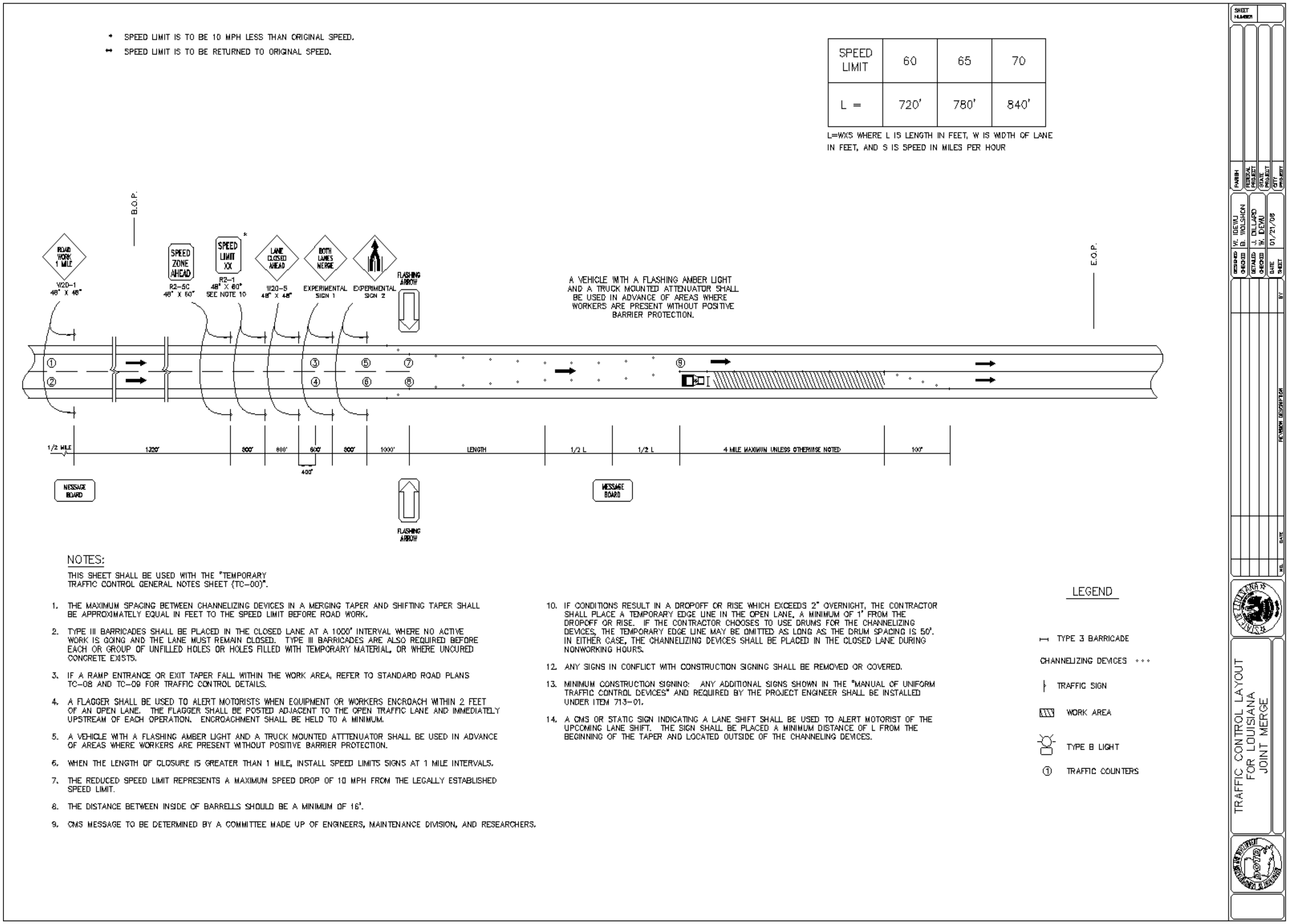
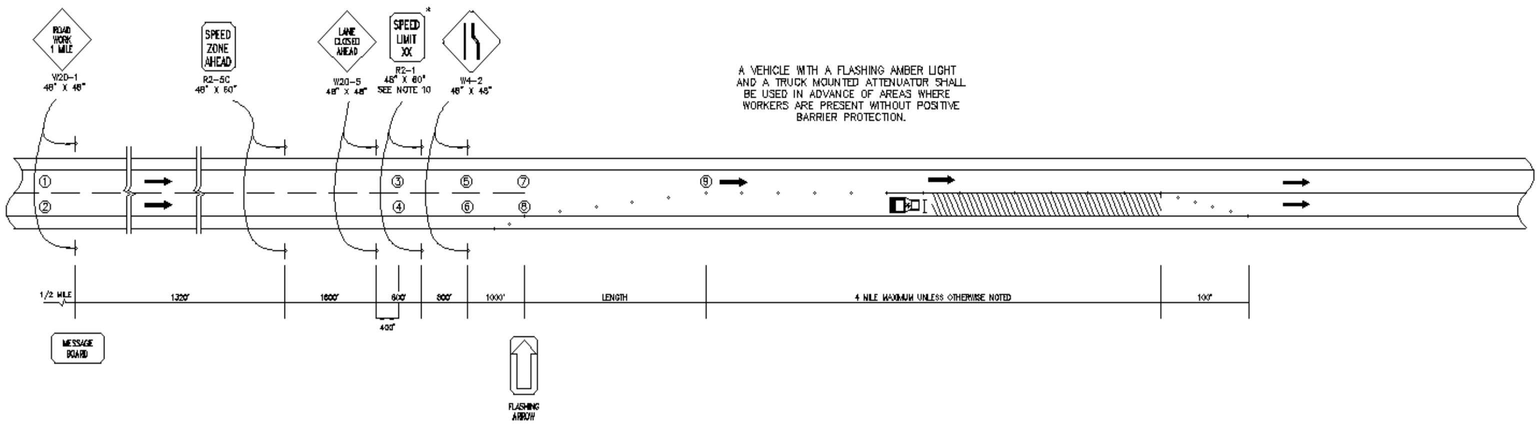


Figure 4
Joint merge configuration

* SPEED LIMIT IS TO BE 10 MPH LESS THAN ORIGINAL SPEED.
** SPEED LIMIT IS TO BE RETURNED TO ORIGINAL SPEED.

SPEED LIMIT	60	65	70
L =	720'	780'	840'

L=WXS WHERE L IS LENGTH IN FEET, W IS WIDTH OF LANE IN FEET, AND S IS SPEED IN MILES PER HOUR



NOTES:

THIS SHEET SHALL BE USED WITH THE "TEMPORARY TRAFFIC CONTROL GENERAL NOTES SHEET (TC-00)".

1. THE MAXIMUM SPACING BETWEEN CHANNELIZING DEVICES IN A MERGING TAPER AND SHIFTING TAPER SHALL BE APPROXIMATELY EQUAL IN FEET TO THE SPEED LIMIT BEFORE ROAD WORK.
2. TYPE III BARRICADES SHALL BE PLACED IN THE CLOSED LANE AT A 1000' INTERVAL WHERE NO ACTIVE WORK IS GOING AND THE LANE MUST REMAIN CLOSED. TYPE III BARRICADES ARE ALSO REQUIRED BEFORE EACH OR GROUP OF UNFILLED HOLES OR HOLES FILLED WITH TEMPORARY MATERIAL, OR WHERE UNCURED CONCRETE EXISTS.
3. IF A RAMP ENTRANCE OR EXIT TAPER FALL WITHIN THE WORK AREA, REFER TO STANDARD ROAD PLANS TC-08 AND TC-09 FOR TRAFFIC CONTROL DETAILS.
4. A FLAGGER SHALL BE USED TO ALERT MOTORISTS WHEN EQUIPMENT OR WORKERS ENCROACH WITHIN 2 FEET OF AN OPEN LANE. THE FLAGGER SHALL BE POSTED ADJACENT TO THE OPEN TRAFFIC LANE AND IMMEDIATELY UPSTREAM OF EACH OPERATION. ENCROACHMENT SHALL BE HELD TO A MINIMUM.
5. A VEHICLE WITH A FLASHING AMBER LIGHT AND A TRUCK MOUNTED ATTTENUATOR SHALL BE USED IN ADVANCE OF AREAS WHERE WORKERS ARE PRESENT WITHOUT POSITIVE BARRIER PROTECTION.
6. WHEN THE LENGTH OF CLOSURE IS GREATER THAN 1 MILE, INSTALL SPEED LIMITS SIGNS AT 1 MILE INTERVALS.
7. THE REDUCED SPEED LIMIT REPRESENTS A MAXIMUM SPEED DROP OF 10 MPH FROM THE LEGALLY ESTABLISHED SPEED LIMIT.
8. THE DISTANCE BETWEEN INSIDE OF BARRELLS SHOULD BE A MINIMUM OF 16'.
9. CMS MESSAGE TO BE DETERMINED BY A COMMITTEE MADE UP OF ENGINEERS, MAINTENANCE DIVISION, AND RESEARCHERS.
10. IF CONDITIONS RESULT IN A DROPOFF OR RISE WHICH EXCEEDS 2" OVERNIGHT, THE CONTRACTOR SHALL PLACE A TEMPORARY EDGE LINE IN THE OPEN LANE, A MINIMUM OF 1' FROM THE DROPOFF OR RISE. IF THE CONTRACTOR CHOOSES TO USE DRUMS FOR THE CHANNELIZING DEVICES, THE TEMPORARY EDGE LINE MAY BE OMITTED AS LONG AS THE DRUM SPACING IS 50'. IN EITHER CASE, THE CHANNELIZING DEVICES SHALL BE PLACED IN THE CLOSED LANE DURING NONWORKING HOURS.
12. ANY SIGNS IN CONFLICT WITH CONSTRUCTION SIGNING SHALL BE REMOVED OR COVERED.
13. MINIMUM CONSTRUCTION SIGNING: ANY ADDITIONAL SIGNS SHOWN IN THE "MANUAL OF UNIFORM TRAFFIC CONTROL DEVICES" AND REQUIRED BY THE PROJECT ENGINEER SHALL BE INSTALLED UNDER ITEM 713-01.

LEGEND

TYPE 3 BARRICADE
CHANNELIZING DEVICES
TRAFFIC SIGN
WORK AREA
TYPE B LIGHT
TRAFFIC COUNTERS

DESIGNED / CHECKED / DETAILED J. DILLARD / CHECKED W. DEVAU / DATE 01/21/05

TRAFFIC CONTROL LAYOUT FOR LOUISIANA RIGHT LANE CLOSURE

TC

Figure 5
Conventional merge configuration

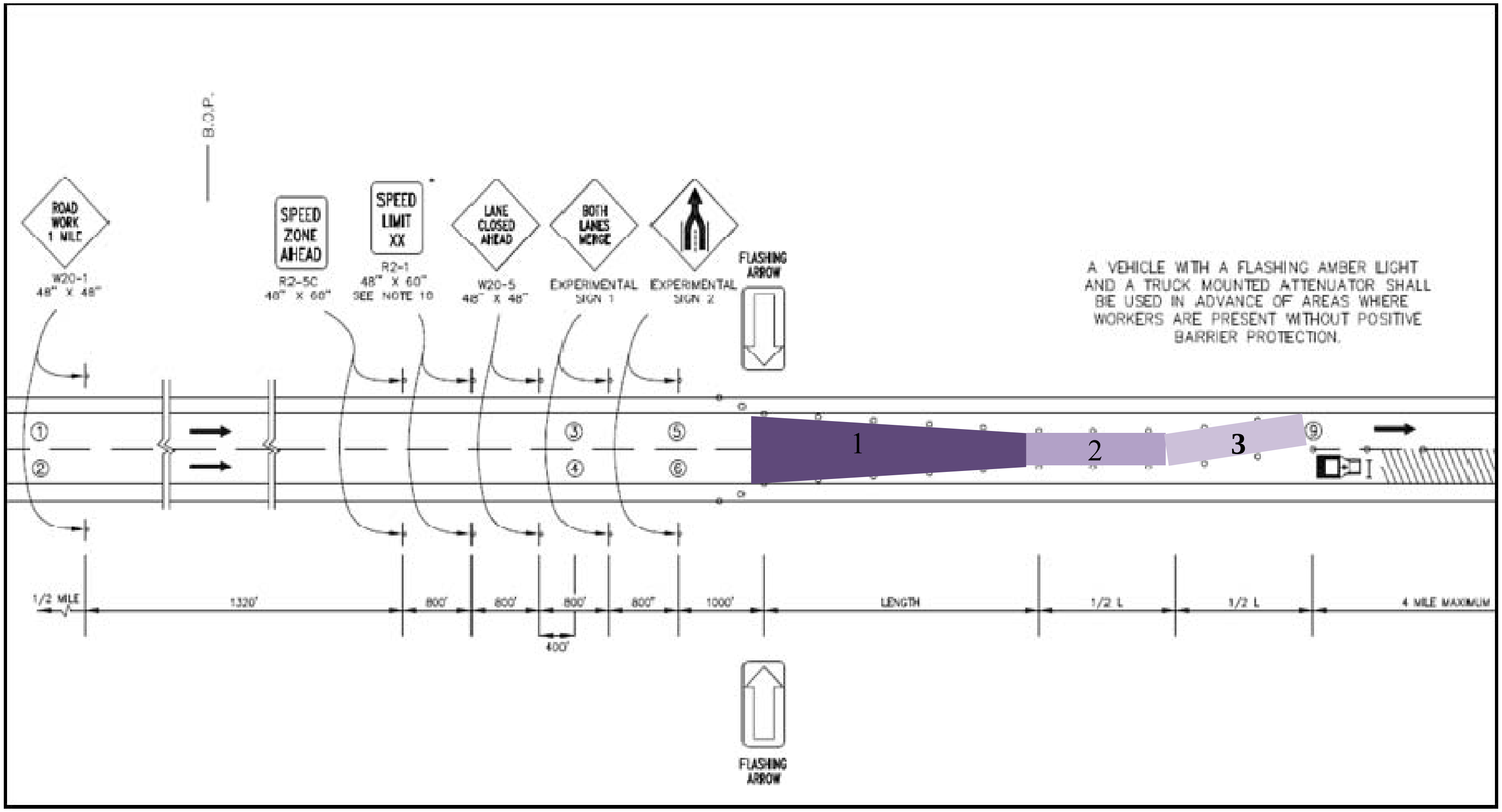


Figure 6
Joint merge traffic control plan with transition zone segment coding

Figure 7
Segments 2 and 3 of the joint merge transition zone

Three CMBs were used during installation and operation of the joint merge configuration. The first was placed one-half mile before the first advance warning sign. The next two were placed 1,500 ft. before the first advance warning sign and 210 ft. before the third transition segment.

The joint merge configuration was tested at the same site twice. During the first field tests, the first message board read “Reduce Speed to 60 mph.” The series of messages displayed on the second message board was “Both Lanes Merge,” “Use Extreme Caution,” and “Road Work Ahead.” All three messages were displayed every three seconds. One of those messages is shown in Figure 8. The last message board near segment three continuously read “Lane Shifts to Left.”

Figure 8
Second changeable message board

Three CMBs were placed in the second implementation of the joint merge and remained until the configuration was removed. Although worded slightly different at the discretion of the Louisiana Department of Transportation and Development (LA DOTD) operation maintenance personnel, the CMBs conveyed the same message to motorists. The first CMB read "Reduce Speed to 60 mph" and the second CMB displayed the following two messages every three seconds, "Lanes Merge to Center" and "Use Extreme Caution." Lastly, the CMB in segment three used a combination of wording and symbols. It read "Lane Shifts" with arrows pointing left underneath the text indicating the lane shifts to the left.

Traffic Control Layout

To maintain consistency between designs so that a compared analysis could be performed, the placement of the signs used in the conventional merge configuration closely matched the placement of the same signs used during the test of the joint merge configuration. The positioning of those signs is outlined in Table 2.

Table 2
Placement of static signs for the conventional and joint merge traffic control plans

Signs	Distance in Advance of Transition Zone	
	Joint	Conventional
"Road Work 1 Mile"	1 mile	1 mile
"Speed Zone Ahead"	3,400 ft.	3,400 ft.
" (Right) Lane Closed Ahead"	2,600 ft.	2,600 ft.
Illustrated Sign (W4-2 or Experimental)	1,000 ft.	1,000 ft.
"Speed Limit XX"	2,600 ft.	1,800 ft.
"Both Lanes Merge"	1,800 ft.	NA

The nature of the two merge configurations required modification to the location of a few advance warning signs. Those signs were the "Speed Limit XX" and the "Both Lanes Merge" sign. When the configuration was changed from the conventional configuration to the joint configuration, the "Speed Limit XX" sign was replaced with a "Both Lanes Merge" sign and relocated 1,600 ft. upstream.

Site Selection

Selection of a suitable site was critical since some roadway elements could not be controlled. An external disturbance such as nearby interchange ramps and unlevel terrain complicates the analysis and can lead to biased results. Selecting the proper test site limits the need to account for the surrounding environment's affects on travel behavior. A set of criteria were used to select the ideal location to perform the study. The ideal location was to have:

- Active construction work on rural freeways;
- Two-to-one lane closures;
- Recurring periods of congestion and queuing;
- Adequate space along the shoulder for set up of data collection devices;
- Limited access to entrance and exit ramps within or near the study area; and
- Relatively straight horizontal and level vertical alignments.

Several sites within approximately 100 miles from Louisiana State University were considered. The site used in this study was on Interstate (I)-55 north of Hammond between mile markers 33 and 36. While the merge configuration experiments were initially developed to accompany routine road maintenance projects, this study did not include analysis of traffic behavior in active work zones because of conflicting schedules between LA DOTD, contractors, and researchers. Instead, "dummy" work zones, work zones without any work present, were set.

Description of the Study Site

To eliminate the effects of roadway curvature, the study was performed on a straight and level segment on I-55. The nearest on ramp was located 250 ft. in advance of the entrance to the study area, and the nearest off ramp was two miles after the study area. The total length of the area where testing occurred was 7,704 ft. According to LA DOTD, the 2007 average annual daily traffic counts north bound on I-55 near the study site was approximately 20,858 vehicles per day (vpd). During normal operations, the posted speed limit is 70 mph, but when lane closures are present the posted speed limit is changed to 60 mph.

The site was visited periodically throughout the duration of the study by researchers, primarily to capture video images of merging events. Evidence of vehicular crashes, such as tire markings, dismembered beacon lights, displaced channeling devices, etc., was also noted. This evidence will be used in a separate safety study currently underway. When lane closures were in place, LA DOTD road-maintenance personnel visited the site at least once a day to ensure traffic control devices were functioning properly. Most days the site was visited once in the evening and once during the day.

Detection Zones

Four detection zones before the transition zone and one detection zone immediately after the transition were established for both configurations. Figure 9 illustrates the location of the zones termed Zone A, Zone B, Zone C, Zone D, and Zone E. The lettering used to identify each zone coincides with the position in progressive order. Therefore, Zone A was the first zone, before the first warning sign, and the following zones progressed in letters to Zone E, which was after the transition from two to one lane was complete. Zone A was positioned before the warning area, and it represents the traffic behavior under normal driving circumstances not influenced by any signage or lane closures.

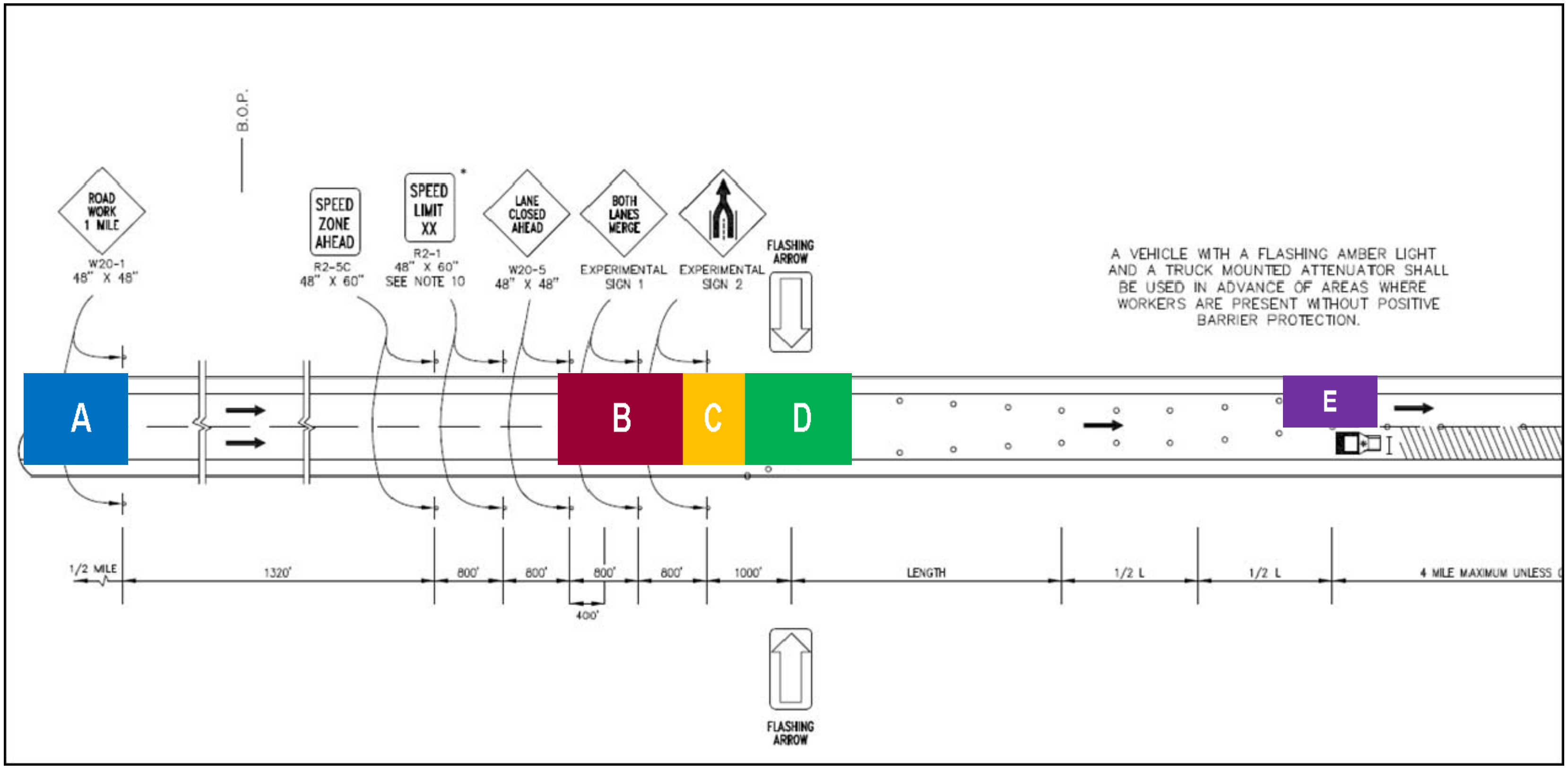
Data Collection Devices

Video recorders and vehicle magnetic imaging recorders (MIRs) were used to record speed, volume, vehicle type, and merging maneuvers. The MIRs are self-contained vehicle sensors that require no external sensors. MIRs are installed under a protective rubber cover in the center of the traffic lane so that motor vehicles pass over the sensor. No physical contact by a vehicle is necessary. The sensors use vehicle magnetic imaging to detect vehicles as they move through the earth's magnetic field. Every motor vehicle has parts that are constructed from iron. When a vehicle passes over the MIRs, the iron parts interfere with the earth's magnetic field. This disturbance creates electrical signal changes in the sensors. As a result, the MIRs can determine vehicle presence, count each vehicle, measure vehicle speed, and record vehicle length. The MIRs also report road surface temperature.

Reliability of the MIRs

The sensors record speeds and vehicle lengths with 90 percent accuracy plus or minus 4 mph and 4 ft. respectively. Vehicle counts are reported to be 99 percent accurate. The maximum storage capacities of the units are advertised as being 300,000 vehicles or 21 days, whichever comes first. Headways are internally derived by the units from the vehicle counts and speed information. The automatic headway adjustments identify vehicles with speeds below 8 mph as stopped vehicles.

Figure 9
Zones used for traffic control plan analysis



Video Recordings

An over-the-counter hard disk drive camcorder was situated on an overpass facing the opposite direction of travel and overlooked the transition zone. The camcorder captured merging events from the beginning of the transition zone to the beginning of the study site.

Figure 10 shows the range in distance the video recorder was able to capture. Video images of merging events were recorded for future qualitative and quantitative analyses and were used as visual supplements to data recorded by the MIRs. Approximately two hours of video were recorded during each site visit by researchers including some visits during the installation and removal of lane closures. This resulted in over 10 hours of video recordings when lane closures were set.

Figure 10
Entry into transition zone of the joint merge

Installation

The enormous amount of effort in the labor-intensive data collection process for this study cannot be understated. Efforts to install MIRs were affected by holidays that generated large amounts of traffic, weather, availability of the LADOTD road-maintenance personnel, and speeding vehicles near the installation crew. The goal of acquiring lane specific traffic information from several zones in the study site required the execution of several safety measures explained next.

Although arrow boards were primarily used as a supplement to static signs during the execution of a merge configuration, they were first used during the installation of the MIR sensors. A truck-mounted arrow board was placed at least one-half mile in advance of the installation area to encourage motorists to use the lane opposite of where the sensors were being installed. For instance, when MIRs where installed in the right lane, the truck-mounted arrow board was positioned in the right lane and displayed an arrow pointing to the left. A minimum of five LADOTD maintenance persons were dispersed evenly from the arrow board to the point of installation. Shown in Figure 11, maintenance personnel flagged motorists in the opposite lane and served as additional security for the installation crew, which usually required three people.

The MIRs were attached to the middle of the lane using the following tools:

- Protective Rubber Cover
- Anchors
- Hammer Drill and 5/8-in. Drill Bit
- Screws
- Washers
- Ratchet Set
- Leaf Blower

An electric hammer drill, powered by a gas generator attached to the back of a truck, was used to drill 2 in. deep holes. During the drilling process, a leaf blower was used to blow away residue created by drilling since it was found on past attempts that settled residue impeded the screwing process. Next screw-anchors were placed in the holes. Finally, the MIRs were incased in the protective rubber cover and attached to the lane using screws, washers, and a ratchet set. This process was repeated seven times at different locations. Images of the sensor and installation process are shown in Figures 12 and 13.

Figure 11
Flaggers near the installation of MIRs

Sensor Placement

The locations selected for sensor placement were governed by the location of existing signs, the sensor's proximity to other sensors in nearby zones, and by areas where most lane changes were likely to occur. Motorists typically respond to information they view as being noteworthy. Therefore, areas near signs that were considered to convey "important information" were targeted as possible locations for sensor placement. Signs that motorists were thought to most likely respond to were the "Lane Closed Ahead" sign, the "Speed Limit XX" sign, and the symbolic right lane closed sign.

Figure 12
Example of the installation process

Figure 13
Attached MIR with protective cover

With the exception of Zone E, which had only one lane and one sensor, a total of two MIR sensors were placed in every zone. The sensors sharing a zone were placed across from each other in the middle of the respective lane. An example of attached MIR sensors are shown in Figure 14 and their zonal locations are listed in Table 3.

Figure 14

Placement of MIRs

Table 3
Placement of MIR sensors for both merge configurations

Zone	MIR Sensors	Distance From the Beginning of the Taper	
		Conventional	Joint
A	1 and 2	1500’ before first advance warning sign	1500’ before first advance warning sign
B	3 and 4	2,200’	2,200’
C	5 and 6	1,000’	1,000’
D	7 and 8	0’	0’
E	9	*-840’	*-1,680’

Note: *Denotes that the distance is measured in the direction of traffic from the beginning to the end of the transition zone.

Sensors 7 and 8 were placed at the entrance of the transition zone, Sensors 5 and 6 were adjacent to the symbolic right lane closed sign, and Sensors 3 and 4 were place in between the “Lane Closed Ahead” and “Speed Limit XX” signs. Sensors 1 and 2 were placed 1,500 ft.

before the “Road Work 1 Mile” sign to record uninfluenced traffic behavior. Lastly, Sensor 9 was placed in the left lane immediately after the transition from two lanes to one was completed.

Data Collection

Work Intensity

The level of work exercised at a site can have a negative impact on the capacity of the roadway, and subsequently affect traffic operations of areas leading up to the transition zone (Dixon, Hummer, & Lorscheider, 1996). The reduction in capacity, due to a highly active work area, could potentially lead to long queues that quickly propagate backwards. A roadway uninfluenced by road work activity was thought to be better suited for the analyses of two merge configurations. Therefore this study was performed at an inactive work zone.

Data Collection Period

The study was performed throughout an eight-month period in which over 600 hours of data were recorded at several locations within the study area. With the aid of the Louisiana Transportation Research Center and the Hammond District of LADOTD, researchers collected data in the north-bound lanes of I-55. Information collected during rainy periods was not used in the analysis as it was thought to introduce unexamined variables.

For 10 days channeling devices and signs were arranged to match the conventional configuration’s traffic control plans for right lane closures. The same location was used for the set up and analysis of the joint merge configuration, which was analyzed twice for a total of 18 days. At least three weeks of normal freeway operations, where lane closures were not present, divided the three data collection periods. This was done to decrease the possibility of traffic behavior transferring from one testing period to the next and biasing the study.

Data Recording

Data collection was undertaken using a combination of techniques based on prior research experience and knowledge gained from experience while completing the study. It was hypothesized that the efficiency of a lane closure was impacted by the total traffic volume and the lane positioning of vehicles as they near the transition zone. Therefore, both configurations’ lanes’ specific volume and speed information were recorded in 60-minute time periods.

Programming Speed Groups in the MIRs

MIRs use speed groups to record and average speeds on an hourly basis. The maximum number of speed groups available for use in the MIRs is 15. Motorists often exceeded the posted speed limit of 60 mph, sometimes traveling in excess of 80 mph. The speed groups in Table 4 were programmed into the units to capture the majority of vehicle speeds in the study site.

Table 4
Programmed speed groups

Speed Group	Miles Per Hour
1	≤ 19
2	20 to 24
3	25 to 29
4	30 to 34
5	35 to 39
6	40 to 44
7	45 to 49
8	50 to 54
9	55 to 59
10	60 to 64
11	65 to 69
12	70 to 74
13	75 tot 79
14	80 to 84
15	≥85

Volume Classification

Typically, volumes are classified as belonging to one of three categories, low, medium or high. To strengthen the analysis in this study, the number of volume classes was doubled resulting in six volume groupings. The highest recorded flow rate was 1,672 vph; therefore, six volume classes were created at increments of 300 vph to give an equal and balanced qualitative representation of the approaching volume's contribution to the operation of the merge configurations. The established volume classes are presented in Table 5.

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Table 5
Volume classification

Volume Class	Vehicles Per Hour
LOW	Below 300
LOW/MEDIUM	300 to 599
MEDIUM	600 to 899
MEDIUM/HIGH	900 to 1199
HIGH	1200 to 1499
VERY HIGH	Above 1499

Data Aggregation and Reduction

The data were extracted from sensors and formatted in a spreadsheet using several ordinal steps. First, the data were grouped by the type of merge configuration, second by time of day, next by zones, then by volume classification, and finally by lane orientation, right or left lane. Statistical comparisons between all groupings as a function of speed and volume were performed at a 95 percent confidence level using T-test and Analysis of Variance (ANOVA) procedures. Time intervals that did not encompass a complete data set were removed from the analysis.

Measures of Effectiveness

The overall objective of the joint merge configuration was to maintain the pre-work zone traffic characteristics that existed before the installment of a lane closure. The introduction of a lane closure was thought to impede traffic operations that would otherwise have relatively safe and uniform speeds unchanging as vehicles travel through roadway segments and minimal lane changes. These flow characteristics were used to select appropriate measures of effectiveness for the study, which were average speed, flow rate, and vehicle lane distribution.

Speed

The joint merge was expected to better maintain speeds in both the open and closed lane as vehicles pass each zone. Therefore, the joint and conventional configuration's average change in speed was compared with respect to zones, lanes, and volume. The statistical tests are described in more detail later in this report.

Queue Discharge Rate

The queue discharge rate occurs during congested periods and is the hourly flow rate of vehicles after capacity is exceeded. In a lane closure capacity study, Jiang (1999) concluded that the queue discharge rate is a better measure of efficiency than flow rates observed during uncongested periods.

Congested periods begin after capacity is exceeded. A common method used in identifying capacity makes use of time-stamped speed data. Previous studies identified capacity as the flow rate just before a drastic decrease in speed followed by a sustained period of low vehicle speeds (Jiang, 1999; Dudek and Richards, 1982; Al-Kaisy, Zhou, and Hall 2000). Maze et al. (2000) points out, current speed-flow relationship models, such as the speed-flow diagrams shown in the *Highway Capacity Manual*, depicts the maximum flow rate occurring when speeds decline by approximately 14 percent. In this study, congested periods were acknowledged by a sharp decrease in speeds of 14 percent or more. The queue discharge rate was the highest observed flow rate during congested periods. All queue discharge rates were averaged and compared across configurations using T-test analyses. An example of one of the selected queue discharge rates used in the analysis is shown in Figure 15.

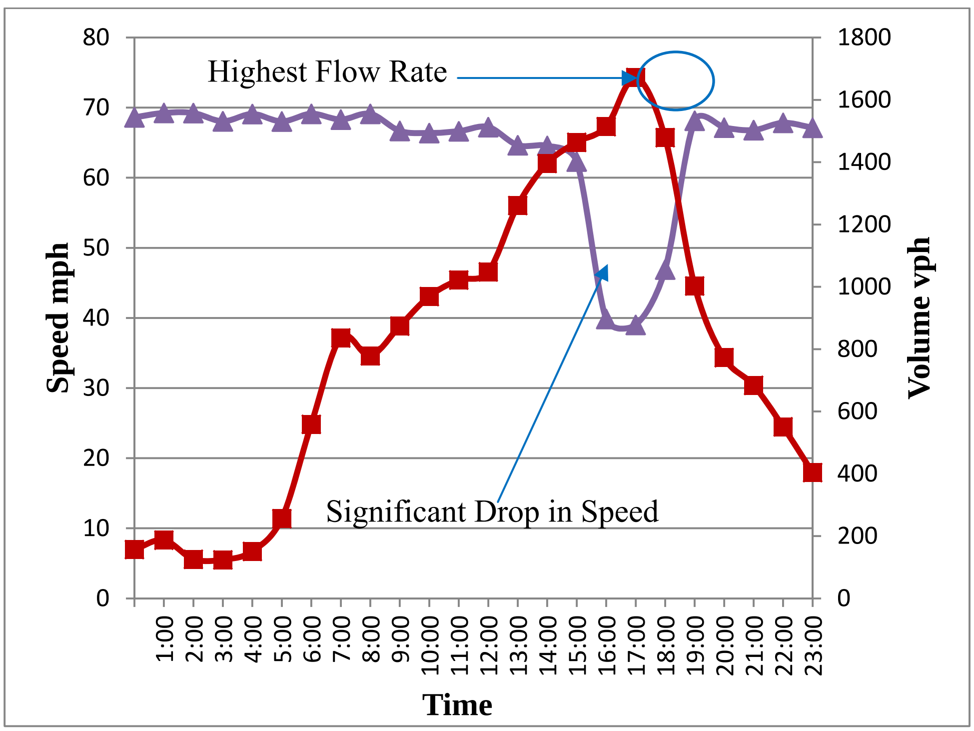

Figure 15

Example of speed/time and volume/time graph used in selecting maximum flow rates

Figure 15 shows a line graph of a speed/time relationship (purple) and a volume/time relationship (red). A significant drop in speed occurred at 15:00 hours and the speed did not recover until 18:00 hours. Therefore, the congested period in this example was from 3:00 p.m. to 6:00 p.m. The highest flow rate observed during the congested period was approximately 1,672 vph. This flow rate was later averaged with other maximum flow rates observed during separate congested periods.

Lane Distribution

Channeling devices used in the joint merge configuration were arranged to produce a balanced lane volume at all zones for all volume levels. Such an occurrence was thought to result in 50 percent of the total volume using the closed lane at every zone during both low- and high-volume periods. The percentage of vehicles observed in the closed lane of both configurations was calculated.

In theory, flow rate of a segment is maximized whenever a 50/50 distribution of vehicles between lanes exists. Past studies have found that less than five percent of motorists enter into the transition zone from the closed lane of a conventional merge configuration (Pigman and Agent, 1988). Analysis of Variance and T-test statistical procedures were used to compare the joint and conventional merge configurations' ability to encourage 50 percent of motorists to continuously travel in the closed lane. The percentages of vehicles in the closed lane of both configurations were analyzed by zone and volume classification.

Several measures were used to determine the joint merge's effect on traffic operations within a work zone's advance warning area. The joint merge configuration was expected to better maintain pre-lane closure traffic operations than its conventional merge counterpart. The following section presents the statistical testing methods used in the comparison of the two configurations. Results from the statistical tests are also discussed and are used in presenting the beneficial aspects of both merge configurations.

DISCUSSION OF RESULTS

This study examined the application of the joint merge configuration to an inactive freeway work zone, and compared it to a configuration that is traditionally used at the same location. Although current merging strategies have shown signs of increased efficiency for traffic operations in work zones, they have yet to effectively address the inadequate use of the closed lane in areas leading up to the transition zone. Full utilization of both the open and closed lanes has been found to increase flow in work zones. Therefore, the joint merge design was configured to achieve a balanced lane volume and encourage the use of both lanes.

The conventional configuration for right lane closures was implemented on I-55 near Hammond, Louisiana for 10 days. At the same site, but on different days, the joint merge configuration was installed twice. A total of 16 days worth of data were collected on the joint merge operation. Although every effort was made to record traffic data at all zones during the study, information in some locations were not obtained due to the malfunctioning of the MIR sensors that could not be resolved by the manufacturer.

The Statistical Package for the Social Science (SPSS) software was used for the analysis of the two configurations. ANOVA tests were performed at the 95 percent confidence level to determine if the merge configurations' average change in speed differed in any zone or for any of six volume classifications. The same tests were applied to traffic traveling in the closed lane to determine if a difference between the two configurations existed in any zone or for any of the six volume classifications. If the tests confirmed that merge configurations were not equal at all levels, further analysis using T-test procedures were performed to specify what factors were different and the levels at which they differed.

This section presents the results of the field tests and statistical procedures used in the analysis of the joint and conventional merge configurations. Comparisons were made by speed, discharge flow rate, and vehicle lane balance using both qualitative and quantitative measures. A more detailed explanation of the comparisons is discussed later.

General Statistics

A general description of traffic statistics for both configurations is explained next. Start times for the MIRs were synchronized to allow temporal correlations on flow characteristics to be identified and evaluated. Flow values observed during each merge configuration test is shown in Table 6.

Table 6
Observed flow values for conventional and joint merge configurations

	Hours of Recorded Data	Total Recorded Volume	Max Volume (vph)	Average Annual Daily Traffic
Conventional	233	149,846	1,672	15,435
Joint	210	147,741	1,602	16,885
Joint 2	164	115,178	1,510	16,855

Testing of the conventional configuration began on August 18, 2008, at 2:00 p.m. and concluded on August 28, 2008, at 7:00 p.m., lasting a total of 233 hours. Traffic statistics were recorded in 60-minute time periods. The total recorded volume showed 149,846 vehicles passed through the location with a peak volume of 1,672 vehicles on August 22, 2008, between 5:00 and 6:00 p.m., and a minimum volume of 49 vehicles on August 25, 2008, between 2:00 and 3:00 a.m. The average annual daily traffic (AADT) count for this study was 15,435 vehicles. A full data set was obtained at Zones D and E, along with data at several locations before Zone D. An abbreviated version of recorded speed data at Zones D and E are shown in Table 7.

Table 7
General speed statistics at Zones E and D

Speed Statistics		Conventional	Joint	Joint 2
Zone D	Mode mph	67	72	67
	Average Speed mph	63	69	61
	85th Percentile Speed mph	74	76	71
Zone E	Mode mph	67	67	65
	Average Speed mph	61	62	63
	85th Percentile Speed mph	68	70	72

At least half the vehicles were in the 65 - 70 mph range or lower. The average speed for all classified vehicles in Zone E was 65 mph with 62 percent of vehicles exceeding the posted speed of 60 mph. The MIRs found 81 percent of the total vehicles were in excess of 55 mph. The mode speed for this traffic study was 67 mph and the 85th percentile was 70 mph.

Less than half the vehicles, approximately 43 percent, in Zone D were traveling in the 65 - 70 mph range or lower. The average speed for all classified vehicles was 69 mph with 81.14 percent vehicles exceeding the posted speed of 60 mph. The MIRs found 91 percent of the total vehicles were traveling in excess of 55 mph. The mode speed for this traffic study was 72 mph and the 85th percentile was 76 mph.

The joint merge configuration was implemented in the field twice. The first occasion began on September 29, 2008, at 2:00 p.m. and concluded on October 8, 2008, at 8:00 p.m., lasting a total of 210 hours. The total recorded volume showed 147,741 vehicles passing through the location with a peak volume of 1,602 vehicles on October 3, 2008, between 5:00 and 6:00 p.m. and a minimum volume of 58 vehicles on October 5, 2008, between 2:00 and 3:00 a.m. The AADT count for this study was 16,885 vehicles.

At least half the vehicles in Zone E were in the 65 - 70 mph range or lower. The average speed for all classified vehicles was 61 mph with 39 percent of vehicles exceeding the posted speed of 60 mph. The sensors found 60 percent of the total vehicles were traveling in excess of 55 mph. The mode speed in Zone E for this traffic study was 67 mph and the 85th percentile was 68 mph. At least half the vehicles in Zone D were in the 65 - 70 mph range or lower. The average speed for all classified vehicles was 63 mph with 57 percent of vehicles exceeding the posted speed of 60 mph. The sensors found 71 percent of the total vehicles were traveling in excess of 55 mph. The mode speed for this traffic study was 67 mph and the 85th percentile was 74 mph.

The second joint merge study began on February 12, 2009, at 2:00 p.m. and concluded on February 19, 2009, at 10:00 a.m., lasting a total of 164 hours. Traffic statistics were recorded in 60-minute time periods. The total recorded volume showed 115,178 vehicles passed through the location with a peak volume of 1,510 vehicles on February 16, 2009, between 5:00 and 6:00 p.m., and a minimum volume of 69 vehicles on February 16, 2009, between 2:00 and 3:00 a.m. The AADT count for this study was 16,855 vehicles.

At least half the vehicles in Zone E were in the 65 - 70 mph range or lower. The average speed for all classified vehicles was 63 mph with 46 percent of vehicles exceeding the posted speed of 60 mph. The sensors found 65 percent of the total vehicles were traveling in excess of 55 mph. The mode speed for this traffic study was 65 mph and the 85th percentile was 72 mph. At least half the vehicles in Zone D were in the 65 - 70 mph range or lower. The average speed for all classified vehicles was 61 mph with 49 percent vehicles exceeding the posted speed of 60 mph. The sensors found 70 percent of the total vehicles were traveling in excess of 55 mph. The mode speed for this traffic study was 67 mph and the 85th percentile was 71 mph.

Lane Distribution

A key element in the operation of the joint merge is the lane distribution of vehicles. It was thought that an evenly balanced traffic stream coupled with a designated point to merge would lead to shorter queue lengths, higher flows, and "smoother" merging events.

The first distribution comparison was performed with respect to volume. A graph illustrating the relationship between percentages of vehicles in the closed lane and total volume in both lanes was plotted for each of the three study zones (Zones A, B, and D). During construction of the graphs, it was noticed that data points appeared to resemble a linear trend. Using least squares estimate procedures, lines representing the data points were constructed as shown in Figure 16.

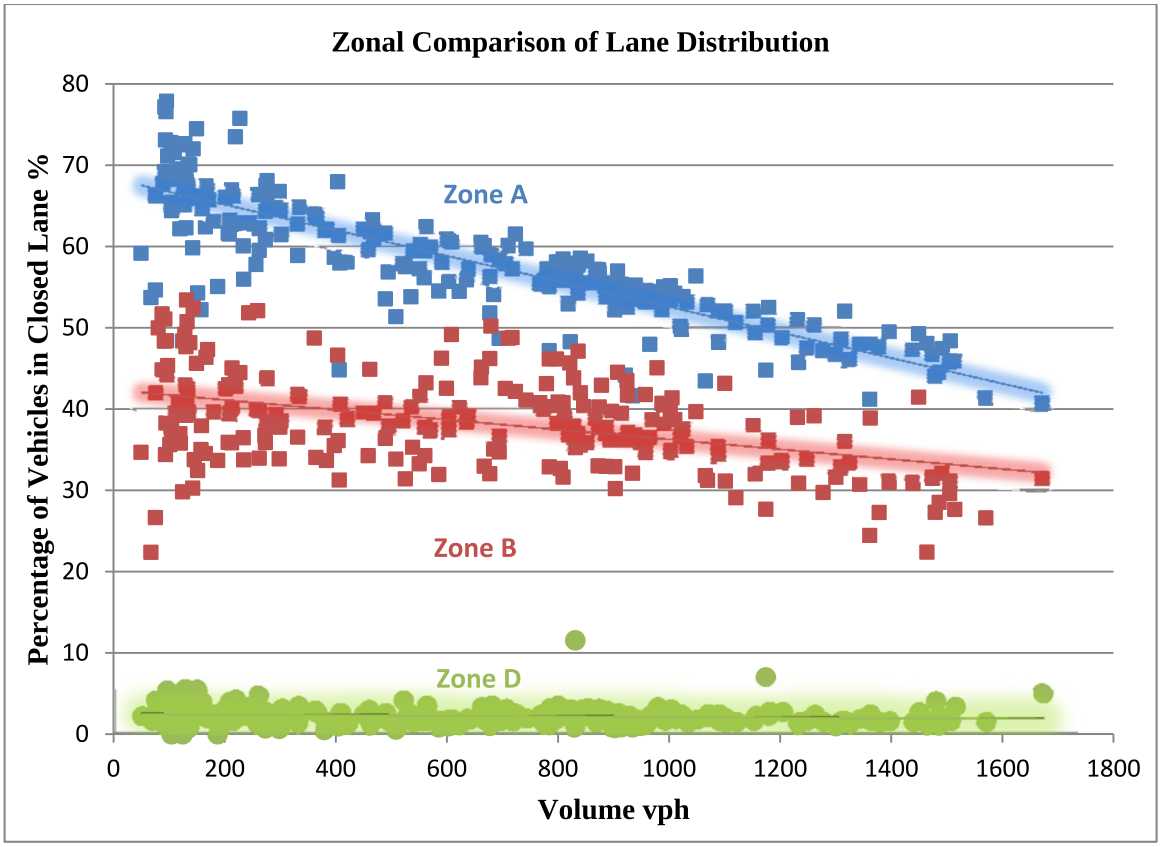

Figure 16

Fitted curves using least squares estimate

Figure 17 illustrates the results of all linear estimates for both configurations used to compare Zones A, B, and D. The zones were distinguished by color and the type of merge configuration. The solid lines represent the joint merge and the dashed lines represent the conventional merge. Zones A, B, and D are represented by the blue, red, and green colors, respectively. The colors used in Figure 17 correspond to the colors used previously in Figure 16.

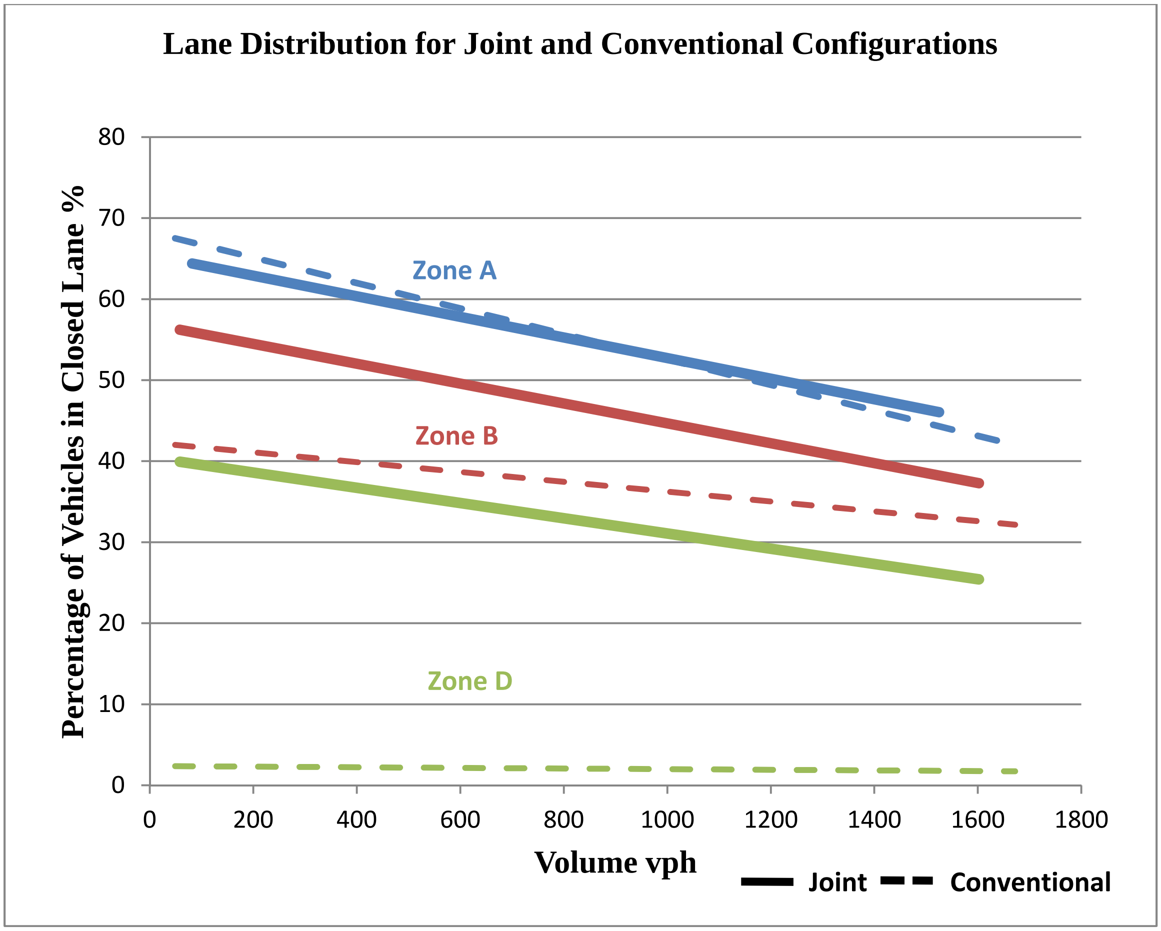

Figure 17
Comparison of lane distribution of vehicles

Distinct differences between the joint merge configuration and conventional merge configuration are illustrated in Figure 17. However, one finding is consistent with both configurations. There was a negative relationship between the percentage of vehicles in the closed lane and total volume in all zones. As volumes increased, the percentage of vehicles that were observed in the closed lane decreased. This suggests that motorists are more likely to travel in the open lane during high volumes. The graph in Figure 17 also provides evidence that opportunities to merge into the open lane were greatest when vehicle densities are low. This suggests during low-volume periods, motorists were comfortable traveling in the closed lane longer before merging into the open lane.

The trends representing the conventional merge showed that the negative relationship was strongest in Zone A and progressively weakened through Zone B, until Zone D where the slope of the curve was approximately zero. This finding suggests that volume has less of an effect on motorists as they near the transition. This is most likely due to lane changing behavior. More than 97 percent of vehicles merge into the open lane before arriving at the transition zone. Since the majority of motorists are found to travel in the open lane, the possibility of the less-dense closed lane being affected by volume increases is small.

Figure 17 also shows a different trend for the joint merge configuration. A linear relationship was observed for the joint merge that remained relatively consistent from Zone A through Zone D. For instance, the linear curve representing Zone A for the joint merge closely parallels the curves in Zone B and Zone D. This suggests that the lane balance to volume relationship was the same in all zones for the joint merge configuration. Meaning the response to an increase in traffic was the same at Zones A, B, and D.

Another difference between the joint and conventional merge configurations was the balance of vehicles in each lane. Zone A represented traffic flow under normal driving conditions prior to the installation of a lane closure. As expected, the percentage of vehicles in the closed lane in Zone A was similar for both configurations. However, the joint merge produced a higher percentage of vehicles in the closed lane in Zones B and D. For example, when the conventional configuration was in use, approximately 42 percent of vehicles were in the closed lane of Zone B for volumes of 200 vph. However, when the joint merge was used, the percentage of vehicles in the closed lane at Zone B increased by 33 percent. Less of a difference is observed at very high volumes of 1,400 vph or more. At these volumes lane balance differences is approximately five percentage points.

The greatest difference occurred in Zone D during periods with volumes of 200 vph or less. In this instance 38 percent of vehicles occupied the closed lane of the joint merge configuration and only two percent in the closed lane of the conventional merge configuration. Similar to Zone B, the differences decreased as volumes increased with the least difference of 23 percent occurring approximately at volumes of 1,600 vph. These findings suggest the joint merge configuration influences a more balanced traffic stream.

Lastly, it was found that vehicles remained in the closed lane longer when in the joint merge configuration. This phenomenon was illustrated in Figure 17 by the space between two curves. For instance, at 800 vph the difference between curves of Zones A and B for the joint merge configuration was approximately eight percent. At the same volume the difference between the curves of Zones A and B for the conventional merge configuration was approximately 18 percent. This suggests more lane changes occurred between Zones A and B and Zones B and D with the conventional merge strategy. The average percentage of vehicles recorded in the closed lanes of Zones A, B, and D are displayed in Table 8.

Statistical testing using ANOVA and T-test procedures were conducted to quantitatively assess the finding of the graphical comparisons. Specifically, the statistical tests were used to evaluate the operation of the merge configurations with respect to speed, volume, and location.

Table 8
Percentage of vehicles traveling in the closed lane

	Type	**Number of Cases**	**Mean**	**Std. Deviation**
Zone A	Joint	29	55	6.89
	Conventional	234	58	8.06
Zone B	Joint	374	48	7.76
	Conventional	234	38	5.86
Zone D	Joint	374	34	9.69
	Conventional	234	2	1.23

The hypothesis that joint and conventional merge configurations influenced the same percentage of traffic to travel in the closed lane was tested using ANOVA. This was accomplished by examining the interaction between several variables thought to effect the operation of a merge configuration. Variables *Type*, *Vclass*, and *Zone* were used in ANOVA tests, where *Type* was defined as the merge configuration (joint and conventional); *Vclass* was the volume classification (Low, Low/Medium, Medium, Medium/High, High, and Very High); and *Zone* was the location within the study site (Zone A, Zone B, and Zone D). The interaction test between *Type* and *Zone* was performed to conclude whether the percentage of traffic recorded in the closed lane of Zones A, B, and D were the same for both configurations. The interaction test between *Type* and *Vclass* gauged if the percentage of traffic recorded in the closed lane during high- and low-volume periods were the same for both configurations. The results of this test are shown in Table 9.

Since all tests were performed at a 95 percent confidence level, percentage values (p-values) smaller than 0.05 suggested the hypothesis should be rejected and that a difference existed between the two merge configurations. All ANOVA tests resulted in highly significant p-values that were less than 0.05. This finding suggests that a significant difference existed between vehicle lane balance in the joint and conventional merge configurations within at least one of the three zones. Likewise, the ANOVA tests shown in Table 9 also revealed that lane balance for both configurations was significantly different for at least one of the six volume classifications.

Table 9
Tests of between-subjects effects for percentage of vehicles in closed lane

Source	**Type III Sum of Squares**	**Df**	**Mean Square**	**F**	**P-value**
Model	2.559E6	36	71093.689	2130.663	.000
Zone * Type	178112.255	4	44528.064	1334.497	.000
Vclass * Type	12758.236	10	1275.824	38.236	.000
Zone * Vclass * Type	8113.479	20	405.674	12.158	.000
Error	48148.481	1443	33.367		
Total	2607521.301	1479			

*Note Type = type of merge configuration, Zone = zonal location, Vclass=demand volume classification

Findings from the ANOVA analysis prompted the execution of a series of T-tests. Vehicles recorded in the closed lane of both configurations differed in at least one of three zones. T-tests were executed at the 95 percent confidence level to determine which zone was significantly different. Table 10 shows the results of the tests. The percentage of vehicles traveling in the closed lane of the joint merge configuration was found to be significantly different at all zones except Zone A. This was expected since Zone A represented normal traffic operations. On average, the joint merge had a higher percentage of vehicles traveling in the closed lane at Zones B and D. These findings were consistent at all volume classification levels. Results from the analyses suggest the joint merge configuration better encouraged the use of the closed lane from the beginning to end of the advance warning area during low- and high-volume periods.

Table 10
Percentage of vehicles in the closed lane at various volume levels

Zone vph		Low (0-300)	Low/Med (300-599)	Med (600-899)	Med/High (900-1199)	High (1200-1499)	Very High (>1500)
A	Joint	63	60	55	51	48	49
	Conv.	66	59	56	51	48	44
B	Joint	55	50	47	46	40	37
	Conv.	40	39	40	37	32	29
D	Joint	42	33	29	35	32	34
	Conv.	2	2	2	2	2	2

Speed Analysis

The next operational factor examined was speed, which was analyzed by lane, zone, and volume. Speed changes between zones were calculated in percentages. For example, if vehicles traveled at speeds of 80 mph in Zone A and dropped to 50 mph in Zone D, the change in speed was -38 percent. Speed changes in the open and closed lanes were analyzed separately, since the closed lane was expected to operate more efficiently than the open lane for a given configuration.

Closed Lane

As mentioned earlier, the size of the data set for each configuration was limited by occasional sensor failures. Zones A and C in the closed lane were missing for both merge configurations. Therefore, the closed lane's speed change was calculated using speeds recorded in Zones B, D, and E. The analysis was used to test the hypothesis that speed changes between zones for all volume classifications were the same for both configurations. Changes in speed in the closed lane were analyzed from Zones B to D and from Zones D to E. Using change-in-speed data, ANOVA tests were performed on the interactions of the *Type*/*Vclass* factors and the *Type/Zone* factors.

Results from the ANOVA test on the closed lane are shown in Table 11. All interaction tests were highly significant, suggesting that speed changes were different as motorists traveled from either Zones B through D or from Zones D to E for the two configurations. The results also revealed the percentage change-in-speed for the joint and conventional configurations were different for at least one of the six volume classifications.

Table 11
Tests of between-subjects effects for percentage change in speed in the closed lane

Source	Type III Sum of Squares	df	Mean Square	F	P-value
Model	168519.857[a]	24	7021.661	26.649	.000
Type * Vclass	104136.373	10	10413.637	39.523	.000
Type * Zone	17423.208	2	8711.604	33.063	.000
Type * Vclass * Zone	8011.010	10	801.101	3.040	.001
Error	298526.428	1133	263.483		
Total	467046.285	1157			

*Note: Type = type of merge configuration, Zone = zonal location, Vclass= Volume classification

T-tests were executed at the 95 percent confidence level to identify the zone(s) where the change in speed was significantly different for both configurations. Results of the speed analysis on the closed lane are displayed in Table 12. During low-volume periods, speeds decreased at a significantly slower rate from Zones B to D in the closed lane of a joint merge configuration. However, at volumes greater than 900 vph, the joint and conventional merge configurations appear to operate the same since the percentage change in speed values were not found to be significantly different. This suggests that the closed lane from Zones B through D of the conventional merge is less efficient during low-volume periods, but operates as well as the joint merge configuration when traffic is dense.

The transition zone received vehicles from both the open and closed lanes. The change in speed from Zones D to E was a measure of the transition zone's efficiency. Shown in Table 12 is the percentage speed change from the closed lane in Zone D to the end of the transition, Zone E. The results from the speed change analysis indicate that the joint and conventional configurations are affected differently by high-volume conditions. Motorists entering the transition zone from the closed lane during low-volume periods increased speeds at a significantly higher rate when the conventional merge configuration was used. This phenomenon was reversed during high-volume periods where speeds increased at a slower rate for the conventional configuration.

Table 12
Percent change-in-speed between zones in the closed lane

Zone vph		Low (0-300)	Low/Med (300-599)	Med (600-899)	Med/High (900-1,199)	High (1,200-1,499)	Very High (>1,500)
B-D	Joint	-6 %	-6 %	-7 %	-8 %	4 %	62 %
	Conv	-15 %	-9 %	-9 %	-9 %	-7 %	11 %
D-E	Joint	4 %	2 %	2 %	4 %	27 %	59 %
	Conv	9 %	6 %	4 %	4 %	3 %	11 %

Open Lane

Statistical tests used to analyze the speed changes in the closed lane were also performed for the open lane analysis. Information was missing from the open lane in Zones B and C. Therefore, speed changes in the open lane were calculated using speeds captured at Zones A, D, and E. Speeds in the open lane were analyzed from Zones A to D and From Zone D to E.

The ANOVA tests on the open lane, shown in Table 13, suggest that observed speed changes from either Zones A to D or from Zone D to E were different for the two configurations. The table also shows that the interaction between factors *Type* and *Vclass* was not significant. Meaning, there was not a significant difference between the percentage change in speed for the joint and conventional configurations that existed for volumes classified as Low, Low/Medium, Medium, Medium/High, High, or Very High. This suggests that the volume alone did not affect traffic operations in the open lane for either configuration.

Table 13
Tests of between-subjects effects for percentage change in speed in the open lane

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Model	83880.405[a]	24	3495.017	50.500	.000
Type * Vclass	1060.760	10	106.076	1.533	.123
Type * Zone	25755.930	2	12877.965	186.077	.000
Type * Vclass * Zone	13304.278	10	1330.428	19.224	.000
Error	51559.646	745	69.208		
Total	135440.051	769			

Results of the speed analysis on the open lane are displayed in Table 14. The joint and conventional configurations operated differently in the open lane when volumes were low. Motorists traveling from Zones A to D experienced a greater decrease in speed when using the open lane of the joint merge configuration at low volumes. Volumes of 900 vph or more were found to produce the same travel behavior between Zones A and D. The percentage changes-in-speed were not statistically different during these high-volume periods. These findings suggest that travel was more efficient in the open lanes when using the conventional merge and when traffic was not dense; however, neither configuration was more efficient than the other when volume conditions were high.

Similar to the findings from the closed lane of Zones D through E, the open lane's speed-change analysis indicated that the joint and conventional configurations are affected differently by low-volume conditions. For example, at volumes less than 300 vph, the joint configuration had a 16 percent decrease in speed; whereas, the conventional configuration had only a nine percent decrease in speed. This suggests that the open lane for the conventional merge configuration was more effective at maintaining speeds during low-volume periods. However, during high-volume periods, the joint and conventional merge configurations operated similarly. Although the change-in-speed values in Table 14 were different for very high volumes above 1500 vph, there was not a statistical difference between Zones D and E for both configurations. This suggests that vehicles entering and exiting the transition zone from the open lane changed speeds in an identical fashion for both configurations. The statistical tests also imply that motorists better maintained speeds as they traveled from Zones A through D in the open lane of a conventional configuration.

Table 14
Percent change in speed between zones in the open lane

Zone vph		Low (0-300)	Low/Med (300-599)	Med (600-899)	Med/High (900-1,199)	High (1,200-1,499)	Very High (>1,500)
A-D	Joint	-16 %	-20 %	-18 %	-20 %	-29 %	-72 %
	Conv	-9 %	-11%	-11 %	-13 %	-17 %	-24 %
D-E	Joint	-7 %	-7 %	-6 %	-5 %	6 %	45 %
	Conv	-4 %	-5 %	-6 %	-5 %	-6 %	13 %

Discharge Flow Rate Analysis

The discharge flow rate was captured at the end of the transition zone in Zone E. As defined earlier, the discharge flow rate was the average of the highest observed flow rates during congested periods. A breakdown of all discharge flow rates used in the analysis is shown in Table 15.

Table 15
Discharge flow rates

Congested Period	**Joint (vph)**	**Conventional (vph)**
1	1,525	1,361
2	1,529	1,570
3	1,527	1,672
4	1,602	
5	1,425	
6	1,461	
7	1,508	
8	1,509	
AVERAGE	**1,511**	**1,534**

T-tests were used to determine if any differences existed between the discharge rates of the two merge configurations. The p-value shown in Table 16 was greater than the rejection value 0.05. Therefore the hypothesis that discharge flow rates were the same for both configurations appears to be true. Although the conventional merge, on average, produced a slightly higher discharge rate of 1,534 vph; it was not statistically different from the average discharge rate of 1,511 vph produced by the joint merge configuration.

Table 16
Joint and conventional merge comparison test for discharge flow rates

	T statistic	Degrees of Freedom	P-value	Mean Difference
Zone E	-.397	9	.700	-23.58333

Table 17 outlines the major findings discussed in the Conclusions section. This section provides inference on what these findings mean and present recommendations based on future applications of the joint merge in the field.

Table 17
Summary of major findings

Description of Findings	**Joint**	**Conventional**
At least 30 percent of vehicles occupied the closed lane during high and low-volume periods	x	
Slightly higher speeds were recorded at all zones.		x
During low-volume periods speeds were better maintained as motorists traveled from Zones A to D in the open lane.		x
During low-volume periods speeds were better maintained as motorists traveled from Zones B to D in the closed lane.	x	
During congested periods, vehicles entered the transition zone at speeds less than 35 mph.	x	
Reduced the number of lane changes.	x	
Relatively even balance of vehicles in both lanes.	x	
Opportunities to merge are greatest when vehicle densities are low	x	x
More than 97 percent of vehicles merge into the open lane before arriving at the transition zone		x
Relatively high discharge rates of 1,500 vph or more	x	x

CONCLUSIONS

The lane closure configuration included in the MUTCD is the current recommended traffic control plan used for work zones. Among its goals is to transition vehicles out of the lane or shoulder occupied by construction to an adjacent lane free of obstructions. It has been theorized, however, that under medium-to-high volume conditions, lane changing maneuvers can decrease traffic flow through the merge area and increase vehicle-to-vehicle conflicts which can then result in an increased numbers of crashes. Over the past decade or so, however, several alternative methods have been suggested, developed, and tested to enhance the safety and efficiency of lane closures in work zones and deal with operational problems such as delay, congestion, and aggressive driving. Interestingly, improvements to the geometric layout of transition zones have not been considered in these methods. In this research project, a new traffic control plan referred to as the joint merge was developed and field tested to assess its effect on flow characteristics within the transition zone.

Joint Merge Development

The idea of the joint merge is to promote an even balance of vehicle volume in the approach lanes leading into the lane drop transition zone. It is theorized that by maintaining a more even volume balance, the number of lane changes within this transition zone would decrease. In the joint merge, this action was expected to be accomplished through the incorporation of several design features.

The most important feature of the joint merge design is its use of a two-sided taper. With it, drivers approaching the transition zone in the adjacent lanes are simultaneously tapered into a single middle lane straddling the roadway centerline. With neither lane having an established priority, it was expected that drivers would be naturally influenced to merge using an alternating pattern. This merging action was hypothesized to create smoother and more uniform conditions which would, in turn, lead to both higher rates flow and a more orderly and safer operations.

Evaluation of the Joint Merge

As part of this research, the conventional merge configuration specified in the MUTCD and the joint merge configurations were evaluated at the same site for approximately 10 days and 18 days, respectively. The test site was located on a segment of I-55 near Hammond, Louisiana. Lane-specific speed and volume information were collected at several established zones using magnetic vehicle imaging recorders affixed to the pavement surface. The data parameters that were recorded of the study site included volume, average speed, flow rate, and lane.

Findings from the Evaluation

The overall conclusions relative to the performance of the joint merge were somewhat mixed. From a quantitative standpoint, the results did not provide overwhelming statistical evidence that that traffic operations were significantly improved as a result of its use. However, from an approach volume distribution standpoint, the joint merge showed a significant impact in its ability to more evenly distribute traffic for a greater utilization of both lanes. While this did not appear to translate into an operational improvement, it is theorized that other benefits such as higher levels of driver satisfaction (from a "fairer" merging process), fewer lanes changes within the approach zone, and a reduction in slowed/stopped queue lengths (by filling both lanes instead of one) may result in qualitative benefits without diminishing the overall flow conditions.

As anticipated, travel speeds varied by configuration and by lane volume. For example, speeds in the conventional merge were more consistent in the open lane than the closed lane. This conclusion was reached by examining the observed decreases in the operating speed as vehicles approached the beginning of the lane-drop transition point. The comparative analyses of flow rates were inconclusive, suggesting the two-sided merge does not substantially increase the amount of traffic that can flow through the transition zone. From a lane utilization perspective, the joint merge showed a marked difference from the conventional MUTCD merge design. This disparity in lane balance between the two configurations suggests that the more evenly balanced joint merge configuration influenced fewer lane changes within and between zones. This may also even suggest that aggressive driving decreased and motorists were comfortable driving through the joint merge traffic control configuration. The following sections discuss each of these measures in more detail.

Speed

The conventional merge was concluded to be more effective at maintaining speed consistency in the open lane and less effective at maintaining speed consistency in the closed lane as vehicles approached the transition zone. Although the finding was not statistically different, the joint merge showed a higher average increase in speed of approximately 10 mph for vehicles traveling through the transition zone (i.e., from Zones D to E). However, this inconsistent finding may be somewhat misleading since speeds at the entrance of the transition zone were consistently lower than all other sections, approximately 30 mph, for the joint merge configuration when volumes were high. The low speeds suggest that drivers were being cautious as they approached the transition zone. This type of behavior may be attributed to unfamiliarity of the joint merge concept and/or the lack of an established right of way heirarchy.

Flow Rate

The comparative analyses of flow rates were similarly inconclusive. The highest flow rates observed at the outflow point of the transition zone for the conventional and joint merge were 1,672 vehicles per hour per lane (vphpl) and 1,602 vphpl, respectively. The joint merge produced an average discharge rate of 1,511 vphpl, while the conventional merge produced an average discharge rate of 1,534 vphpl. However, this difference was not found to be significant in any of the cases.

Vehicle Lane Distribution

Previously, Figure 17 showed the relationship between total volume and the percentage of vehicles in the closed lane. The percentages for Zone A suggest that under normal driving conditions, drivers were more likely to change lanes to overtake slower moving vehicles. However, this behavior was less pronounced as vehicles approached the transition zone under the conventional MUTCD configuration. The percentage of vehicles using the closed lane during low-volume periods did not differ significantly from the percentage of vehicles using the closed lane during high-volume periods. Thus, it may be concluded that volume had a minimal effect on vehicles in the closed lane of a conventional traffic control plan.

Drivers also appear more likely to merge into the open lane as they approach a conventional merge configuration transition zone. In this study, the majority of motorists merge into the open lane, before reaching Zone B, approximately 2,200 ft. before the transition from two to one lane began. This was thought to be related to the signage used in the advance warning area also giving evidence that drivers were in compliance with the signs and merged into the open lane during both low- and high-volume periods. Merging early during congested periods presents the undesirable situation of one lane being over utilized and the other being underutilized. Such conditions have been linked to the problems of long queues, aggressive driving, and delays at work zone entrances.

Similar to a conventional merge, vehicles traveling in the closed lane of the joint configuration appeared to be negatively affected by volume. Unlike the conventional merge, the study results suggest that this relationship remained relatively unchanged as vehicles approached the transition zone. The rate at which the vehicle percentages changed in the closed lane at Zone A was found to be proportional to the change observed in Zones B and D. Combined, this suggests that the lane use behavior observed during the joint merge operation was very similar to lane use behavior during normal freeway operations. This consistency also may suggest that the joint merge configuration actually creates an environment of minimal lane changes. Since neither lane has a clear advantage over the other, it would be reasonable to expect lane use to remain consistent until the transition zone, creating a more balanced distribution. Under these conditions, it may be possible to achieve a condition in which drivers would share merging responsibility until reaching the designated merging location. This lessening could also have the benefit of the disruptive effects of aggressive driving, which is defined by the National Highway Traffic Safety Administration (NHSTA) as “a progression of unlawful driving acts such as: speeding, improper or excessive lane changing, and improper passing” (National Highway Traffic Safety Administration 1998).

On average, 43 percent of vehicles entering the transition zone traveled in the closed lane of the joint merge configuration compared to only 18 percent in the closed lane of the conventional merge. This disparity in lane balance provides evidence that the more evenly balanced joint merge configuration influenced fewer lane changes within and between zones. This suggests that aggressive driving decreased and motorists were comfortable driving through the joint merge traffic control configuration.

Concerns with the Joint Merge

While the experiments also showed reasons to be cautious about the joint merge, these results suggest that it was not nearly as confusing, dangerous, and disruptive as feared by some. However, more study is needed prior to systematically confirm these anecdotal findings prior to recommending its wider application.

One of the initial concerns with the joint merge appears to have been reduced based on the outcomes in this work. That is, priority must be assigned to a lane; otherwise, drivers will become confused and crashes may occur. While a full safety analysis will still need to be taken, there were no reported crashes that were a direct result of the joint merge configuration during the study periods. A review of video recordings made during some periods of operation also revealed that drivers approaching the transition entrance tended to situate themselves so that orderly merges would occur. In many instances the movements of the leading vehicle in a platoon was followed by trailing vehicles. As a result, the location at which vehicles began to merge varied from platoon to platoon. Empirical observation also suggested that, on average, merging started after the experimental sign 1,000 ft. in advance of the transition zone and was completed shortly after the taper began within a distance of approximately 400 ft. Many truck drivers tended to complete the merge and travel in the middle of two lanes before entering the transition zone. However, it was more common to observe passenger cars merging later.

Overall, the intended purpose of the joint merge appeared to be accepted and understood by the majority of drivers traveling through the area. An optimal length to affect the most efficient joint merging process will also require further research and evaluation since most drivers appeared to complete the merge before reaching the halfway point of the transition zone. Thus, a shorter taper may or may not increase the effectiveness of the joint merge.

Unexpected Findings

During the analyses it was observed that data from some vehicles were not recorded by the MIRs in either lane at Zone D. This suggests that vehicles occasionally traveled between the fields of both MIRs. This condition may have also meant that some vehicles may have completed the merge before entering the transition zone of the joint merge configuration. This is not ideal since the joint merge was designed to encourage drivers to use both lanes until reaching the taper and begin merging within the transition zone.

It was also observed that vehicles undetected by MIRs increased with volume, suggesting that during high-volume periods drivers may have been more likely to begin merging before reaching the transition zone. This may have also been due to unfamiliarity of the joint merge concept and motorists not knowing where to begin merging after passing the experimental sign.

Another unexpected observation of the joint merge configuration occurred when a substantial drop in speed (approximately 25 mph) was observed in Zone B. The drop in speed appeared to occur near the "Both Lanes Merge" sign in Zone B and when flow conditions changed from uncongested to congested. This is most likely due to the unfamiliarity with the joint merge concept. Since this was the first study of its kind examined in U.S. work zones, drivers seemed to have taken a more cautious approach to merging with other vehicles. Although seemingly intuitive to most, the potential confusion caused by the desired movement may have resulted in some drivers decreasing speeds. The drop in speed of one vehicle is thought to have transferred to trailing vehicles, which may have attributed to a significant drop in speed near the "Both Lanes Merge" sign during high-volume periods.

RECOMMENDATIONS

The results of this research did not show a significant difference in the discharge rate as vehicles traveled up to and through the transition zone. The modification of a few elements such as repetitive signage in the traffic control plan of the joint merge may yield more definitive results. It is expected that improved traffic behavior and efficiency would result from rewording the "Both Lanes Merge" sign to read "Stay in Your Lane." This may encourage drivers to stay in one lane to create an orderly flow of traffic and decrease the weaving that was sometimes observed in the video recordings and may have resulted from driver confusion.

It is suggested that a descriptive sign legend be attached to the experimental joint merge sign shown in Figure 2. By specifying the merging distance with wording such as "Ahead" or "1,000 ft." placed underneath the experimental sign shown, drivers may be encouraged to continue in their lane until reaching the transition zone. This modification to the sign is recommended for future joint merge applications.

Communication/public information efforts of the joint merge and its associated desired movement were not messaged through any media. To maximize the efficiency of the joint merge configuration, it is suggested that the joint merge concept be more widely communicated to potential facility users.

When compared to the conventional merge configuration, the joint merge was observed to produce a more even balance of vehicles in each lane. Equally distributing vehicles by lane was expected to encourage motorists to travel in their respective lane until reaching the transition zone entrance and subsequently create a natural alternating merging pattern. Although an even distribution did occur during the joint merge test, it was not maintained as volume increased. However, the distribution of vehicles at all volume levels was found to be more evenly balanced when using the joint merge configuration and is thought to have influenced fewer lane changes.

An even balance of vehicles was also thought to increase overall flow in both lanes, thereby establishing a more efficient lane closure design. Generally, it is thought the joint merge improved the efficiency of the closed lane by better maintaining speeds in the closed lane during high- and low-volume periods. This increased efficiency of the closed lane created a denser traffic environment near the transition zone entrance and resulted in a less efficient open lane. The conventional merge better maintained speeds as motorists traveled in the open lane. By combining the positive effects of the joint merge configuration on the closed lane with its negative effect on the open lane, it was found that the overall operation of the joint configuration, with regards to flow rate, was similar to the operation of the conventional configuration.

While no conclusive findings could be made relative to its effect on capacity, the video recordings and lane usage data suggest that the joint merge strategy was understood and well received by most drivers. This would be suggestive of effective design. This sentiment is echoed in discussions with potential and past joint merge facility users. Although a formal questionnaire survey was not administered to drivers, comments from a motorist who traveled through the study site when the joint merge was installed were sent to researchers.

The joint merge traffic control plan is suited for use in work zones with two-to-one lane closures as it has demonstrated the ability to decrease the number of lane changes, decrease aggressive maneuvers, and maintain orderly traffic behavior in advance of the work zone. More research regarding the supplemental wording to the experimental sign and the recommended changes to the joint merge traffic control plan is also suggested. It is thought that these changes could result in a better understanding of the joint merge concept and, ultimately, a safer and efficient use of roadways.

ACRONYMS, ABBREVIATIONS, AND SYMBOLS

AADT	Annual Average Daily Traffic
AASHTO	American Association of State Highway and Transportation Officials
ANOVA	Analysis of Variance Analysis
CDOT	Connecticut Department of Transportation
CMB	Changeable Message Boards
FHWA	Federal Highway Administration
LADOTD	Louisiana Department of Transportation and Development
LTRC	Louisiana Transportation Research Center
MUTCD	Manual of Uniform Traffic Control Devices
ROW	Right of Way
SPSS	Statistical Package for the Social Sciences
TTC	Temporary Traffic Control
VMIR	Vehicle Magnetic Imaging Recorders
VPD	Vehicles per Day

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