Behavior Study of Merge Practices for Drivers at Work Zone Closures

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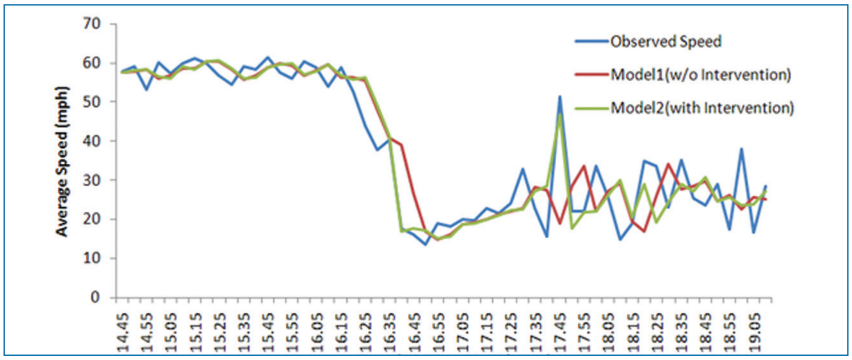
Final Report
June 2011

SWZDI
Smart Work Zone Deployment Initiative



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About SWZDI

Iowa, Kansas, Missouri, and Nebraska created the Midwest States Smart Work Zone Deployment Initiative in 1999 and Wisconsin joined in 2001. Through this pooled-fund study, researchers investigate better ways of controlling traffic through work zones. Their goal is to improve the safety and efficiency of traffic operations and highway work.

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16. Abstract

The purpose of this project was to determine which driver behaviors result in the greatest reduction of capacity with work zone lane closures. Traffic and safety experts believe that driver behaviors, such as forcing late mergers, tailgating, queue jumping in the closed lane or on the shoulder, and other aggressive behaviors have the greatest impact on maximum flow rates. Other behaviors that create excessive headways or slow speeds can also reduce maximum flow in the taper. The objectives of this project were to identify and document driver behaviors that are the most detrimental to work zone traffic flow and safety.

Data were collected at freeway work zones for six days to identify behaviors that affected work zone safety and operations, which included forced and late merges, lane straddling, and queue jumping. Queue jumping occurs when a driver already in the open lane decides to jockey for a better position by moving to the closing lane and passes one or more vehicles before merging back to the open lane.

A total of 30 vehicles queue jumped during the study period. However, vehicles only improved their position in most cases by one vehicle. The queue jumping also resulted in four forced merges, eight late merges, and four late forced merges, indicating that queue jumping has an impact on operations. In addition, queue jumping appeared to evoke aggressive behavior by other drivers, which was manifested by lane straddling and, in some cases, vehicles physically trying to block queue jumpers.

Lane straddling occurs when drivers move to straddle the lane line separating the open and closing lanes with their vehicles. Drivers who lane straddle attempt to prevent vehicles behind them from late merging or moving ahead of them in the queue.

The lane straddling incidents observed in this study often involved several vehicles. Of the 51 incidents that were noted, lane straddling resulted in one forced merge, two late merges, and 14 forced late merges. The main operation impact is that lane straddling creates forced merges that may not have otherwise occurred. In addition, in several cases, drivers who engaged in lane straddling in this study ended up slowing down the entire queue behind them, as they attempted to prevent a driver behind them from using the space they left when they moved over to lane straddle.

This study identified behaviors that compromise safety in work zones. Forced merges, which are discussed as operational problems, are also safety problems, because a driver behind a forced merge has to slow or, in some cases, take some evasive action to avoid colliding with the merging vehicle. Queue jumping also compromises safety, because it creates forced merges and often resulted, in this study, in aggressive actions by other drivers.

Lane straddling can also compromise safety by creating forced merges that may not have otherwise occurred. Lane straddling also resulted in several other safety-compromising behaviors: drivers using the shoulder to pass lane-straddling vehicles, drivers attempting to merge into the space previously occupied by the lane-straddling vehicle and resulting in the lane-straddling driver attempting to physically block the merging vehicle, and, in one case, drivers racing abreast until reaching the arrow board, where a forced merge occurred.

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BEHAVIOR STUDY OF MERGE PRACTICES FOR DRIVERS AT WORK ZONE CLOSURES

Final Report
June 2011

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

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EXECUTIVE SUMMARY

A large number of lane miles are under construction during the peak summer roadway usage season in Iowa each year. Coupled with increased seasonal traffic volume, work zones become points of congestion that can lead to driver frustration and aggressive driver behavior.

As flow through the work zone is reduced, the relative traffic safety of the work zone is also reduced. Work zone queues are commonly hampered by rear-end crashes and sideswipe crashes. However, because work zone status is only recorded within the work zone itself, and crash data do not record the presence of a work zone upstream of the work zone,, the number of crashes resulting from work zone queues, traffic flow shock waves, and sudden lane changes is unknown.

Improved work zone flow will improve safety and work zone flow rates, and are dependent on the behavior of individual drivers. By reinforcing and enforcing positive lane closure merging behavior, both safety and the capacity of work zones can be improved.

The purpose of this project was to determine which driver behaviors result in the greatest reduction of capacity. Traffic and safety experts believe that driver behaviors, such as forcing late mergers, tailgating, queue jumping in the closed lane or on the shoulder, and other aggressive behaviors have the greatest impact on maximum flow rates. Other behaviors that create excessive headways or slow speeds can also reduce maximum flow in the taper. The objectives of this project were to:

- Identify the driver behaviors that are the most detrimental to work zone traffic flow
- Document the frequency of such behaviors
- Determine the impact on capacity reduction
- Identify behaviors that have a direct negative impact on safety
- Develop strategies to modify aberrant driver behavior

Data were collected at a freeway work zones for six days from May to September of the 2010 construction season. Data were collected several additional days, but were not used in the analysis for various reasons. After the first three days of data collection, the research team decided they needed to change the videotaping set-up, so those days were not used.

Data were collected for one day at a different site, but such low volumes resulted in the data not being useful. And finally, data were collected one additional day, but due to rain and wet pavement, the team decided the data were not comparable to the other days that were collected under dry pavement conditions.

The team identified and extracted operational and safety issues through manual observation of the video images for the six days. The team also extracted speed and volume from the video data.

These are the operational issues that the team identified:

- Forced and late merges
- Lane straddling
- Queue jumping

Queue jumping occurs when a driver already in the open lane decides to jockey for a better position by moving to the closing lane and passes one or more vehicles before merging back to the open lane. Queue jumping is expected to affect traffic operations for several reasons.

A total of 30 vehicles queue jumped during the study period. However, vehicles only improved their position in most cases by one vehicle. The queue jumping also resulted in four forced merges, eight late merges, and four late forced merges, indicating that queue jumping has an impact on operations.

In addition, queue jumping appeared to evoke aggressive behavior by other drivers, which was manifested by lane straddling and, in some cases, vehicles physically trying to block queue jumpers.

Lane straddling occurs when drivers move to straddle the lane line separating the open and closing lanes with their vehicles. Drivers who lane straddle attempt to prevent vehicles behind them from late merging or moving ahead of them in the queue.

The lane straddling incidents observed in this study often involved several vehicles. Of the 51 incidents that were noted, lane straddling resulted in one forced merge, two late merges, and 14 forced late merges. The main operation impact is that lane straddling creates forced merges that may not have otherwise occurred. In addition, in several cases, drivers who engaged in lane straddling in this study ended up slowing down the entire queue behind them, as they attempted to prevent a driver behind them from utilizing the space they left when they moved over to lane straddle.

This study identified behaviors that compromise safety in work zones. Forced merges, which are discussed as operational problems, are also safety problems, because a driver behind a forced merge has to slow or, in some cases, take some evasive action to avoid colliding with the merging vehicle.

Queue jumping also compromises safety, because it creates forced merges and often resulted, in this study, in aggressive actions by other drivers.

Lane straddling can also compromise safety by creating forced merges that may not have otherwise occurred. Lane straddling also resulted in several other safety-compromising behaviors: drivers using the shoulder to pass lane-straddling vehicles, drivers attempting to merge into the space previously occupied by the lane-straddling vehicle and resulting in the lane-straddling driver attempting to physically block the merging vehicle, and, in one case, drivers racing abreast until reaching the arrow board, where a forced merge occurred.

In addition to the behaviors listed above, several other safety-compromising behaviors were noted:

- Seven regular vehicles, two construction vehicles, and one police officer made U-turns in the median
- In one instance, a merging vehicle merged in the area occupied by a motorcycle
- In another situation, two vehicles used the left shoulder to pass other vehicles

Several statistical models were developed to attempt to explain the impact of forced and late merges on work zone operations as described in Chapter 6.

Finally, techniques that have been used by others to address work zone safety and operations are summarized in Chapter 7. And, recommendations about the best options in Iowa are provided in Chapter 8.

1. INTRODUCTION

1.1 Background

About 20 percent of the US National Highway System is under construction during peak summer roadway season (Heaslip 2006). Coupled with increased seasonal traffic volume, work zones become points of congestion that can lead to driver frustration and aggressive driver behavior. About 50 percent of highway congestion is nonrecurring, and work zones contribute almost 24 percent of non-recurring delay (Heaslip 2006).

Consequently, improving capacity and level of service and reducing work zone crashes and conflicts is a concern for roadway agencies.

1.2 Factors Affect Capacity and Operations

Heaslip et al. (2007) summarized available information about measuring capacity in a work zone. They indicated that the calculation of demand and capacity for work zones are difficult. They also indicated that different researchers define capacity differently. Some use mean queue discharge flow rate, while others define work zone capacity as traffic flow rate at the onset of congested conditions. Capacity and traffic operations in a work zone are influenced by a number of factors as described in the following sections.

Work Zone Configuration

Maze et al. (2005) identified several variables that affect work zone capacity. The first was work zone lane configuration. Features related to work zone configuration include total number of lanes, number of lanes left open through the work zone, location of open/closed lanes, and geometry (such as, grade, presence of horizontal or vertical curve, lane width, and shoulder type and width). They noted that when one or more lanes are closed, the remaining lanes have less capacity than normal through-lanes. The researchers also indicated that, because the right lane on a multi-lane facility normally carries more traffic, a right-lane closure decreases capacity to a greater degree than a left-lane closure.

Driver Familiarity

Driver characteristics can also affect work zone capacity. Driver experience and familiarity leads to shorter headway and, as a result, higher capacity. This is for driver experience with work zones in general, as well as familiarity with a particular work zone. Consequently, the duration of the work zone can be an important factor. The longer a work zone is in place, the more familiar regular users of the system become, leading to shorter headways and higher capacity.

Heaslip et al. (2007) evaluated driver behavior in work zones and then developed simulation models of driver behavior in work zones. They simulated 1,000 repeated vehicles and found that drivers who are familiar with the work zone are less likely to be forced into late merges and that, when they are, they have a higher merge success rate than non-familiar drivers. The average speed shift for familiar drivers (during peak periods) was 10.4 mph, compared to the average speed shift for off-peak periods, which was 12.9 mph.

Merge Behavior

Maze et al. (2005) also suggest that the *location* of the merge affects capacity and operations. They suggest that drivers merging upstream of a lane closure increases capacity more than late merging. Drivers who do not follow the expected merge discipline and skip to the head of the queue, often creating a forced merge, leads to increased crash risk and turbulence, which diminishes any efficiency gained by early merges.

All it takes is one aggressive driver to force their place in the head of the line at the taper to turn the free flow into a queue operating at a much lower flow queue discharge rate. The maximum flow of a work zone with a lane closure is governed by the flow at the taper point, and, if drivers line-up in single file ahead of the taper, the maximum flow can approach the maximum capacity of an open freeway lane, as traffic flows smoothly through the taper. On the other hand, if merging takes place near the taper, the flow entering the work zone taper is turbulent and maximum flow at the taper is reduced.

In their simulation study of driver behavior in a work zone, Heaslip et al. (2007) also found that merges occurring in the early and middle zones had a higher merge success rate than those occurring in late merge zones.

Heaslip et al. (2007) conducted and summarized several years of field-based work-zone research and made a number of observations. They indicate that drivers have varying preferences for early or late merges based on their willingness to respond to upcoming lane restrictions and their own level of aggressiveness in forced merges. The ability of a driver to merge successfully is based on their ability to react and adapt to individual elements of work-zone strategies. Merging behavior is also influenced by the accommodating vehicle driver’s ability to react to the merging vehicle and their level of aggressiveness and accommodation. Merging behavior affects capacity because interactions between vehicles force speed shifts in following vehicles in driver attempts to avoid conflicts with the vehicle ahead of them.

Heaslip (2006) developed algorithms to model merging behavior based on field observations. Based on outputs from a fuzzy inference system, he defined the probability of a successful merge as a function of merging and accommodating driver aggressiveness as shown in Table 1.1.

Table 1.1. Probability of merge success (information source: Heaslip 2006)

Merging Driver Aggressiveness	Accommodating Driver Merge Accommodation High	Medium	Low
High	Yes	Yes	No
Medium	Yes	No	No
Low	No	No	No

Enforcement

Level of enforcement is the last factor mentioned by Maze et al, (2005), although they do not provide additional explanation. McDonald et al. (2003) evaluated the effectiveness of extra enforcement in work zones. They indicate that very little is known about the benefits of enforcement. Some believe that enforcement supports smooth behavior leading to improved traffic flow.

Other Factors

Other factors also affect work zone capacity and operations. Traffic characteristics, such as percentage of large trucks also affect work zone operations. The presence of workers will also affect work zone operations as drivers adjust their speeds.

1.3 Research Objectives

As flow through the work zone is reduced, the relative traffic safety of the work zone is also reduced. Work zone queues are commonly hampered by rear-end collisions and sideswipe crashes. However, because crash data do not record the presence of a work zone upstream of the work zone (and work zone status is only recorded within the work zone itself), the number of crashes resulting from queues, traffic flow shock waves, and sudden lane changes is unknown.

Improved work zone flow will improve safety and work zone flow rates, and are dependent on the behavior of individual drivers. By reinforcing and enforcing positive lane closure merging behavior, we can improve both safety and the capacity of work zones.

The purpose of this project is to determine which driver behaviors result in the greatest reduction of capacity. Driver behaviors or practices, such as forcing late mergers, tailgating, queue jumping in the closed lane, and passing on the shoulder, as well other aggressive driving behaviors, have the greatest impact on maximum flow rates and cause crashes, property damage, injuries, and fatalities in our roadway work zones.

Other behaviors that create excessive headways or slow speeds can also reduce maximum flow in the taper, compromising road safety. The objectives of this project were to:

- Identify the driver behaviors most detrimental to work zone traffic flow
- Document the frequency of such behaviors
- Determine the impact on capacity reduction
- Identify behaviors that have a direct negative impact on safety
- Develop strategies to modify to aberrant driver behavior

2. SITE SELECTION

The team contacted the Iowa Department of Transportation (DOT) and obtained a list of multi-lane projects that were scheduled to be let in 2010. Sites where bids had been let as of May 2010 were highlighted, the team reviewed work zone construction plans, and, then, they located sites using Google maps to determine surrounding characteristics and roadway geometry.

Feasible sites were selected based on the following factors:

- Work zone would be in operation for a month or more, so that repeated site visits could be made
- A location could be identified in the work zone traffic control plan where the video trailer could be set up away from moving traffic
- Site was 3 hours or less from Ames, Iowa, so that multiple site visits were feasible
- Two-way traffic was maintained throughout construction (no road closures with alternating traffic)
- Traffic volumes were sufficient that queuing or congestion was likely at times
- Right-lane closure (Heaslip et al. 2007 indicated right lanes carry more traffic, so they decrease capacity to a greater degree than left-lane closures)

After selecting several feasible locations, the team made site visits and confirmed with the Iowa DOT that the work zone sites would be operational by June 1, 2010. The team selected two sites on I-35 that met the project requirements, as shown in Figure 2.1.

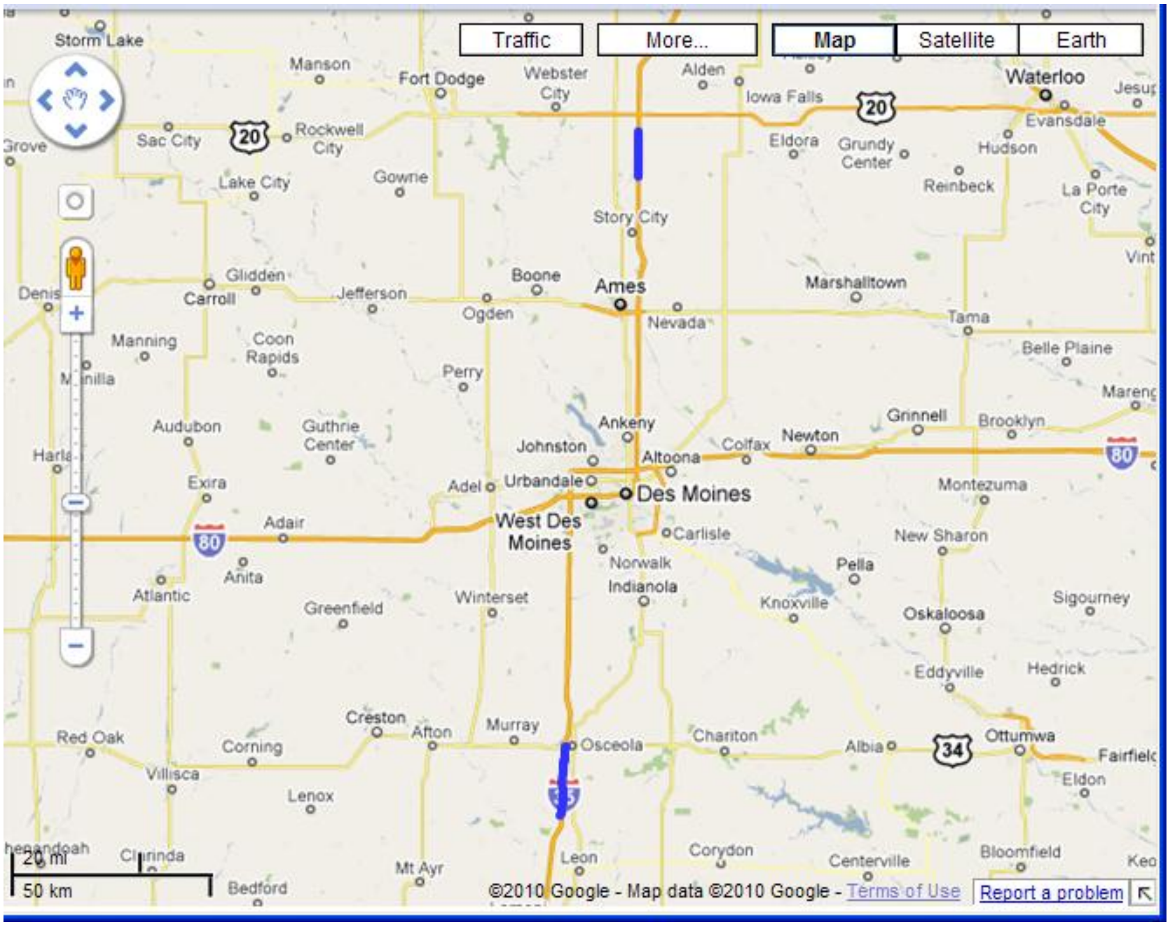


Figure 2.1. Locations of selected sites on I-35 highlighted with heavy blue lines

The northern site started 0.1 miles north of IA 175 and terminated 2.0 miles south of US 20. The project involved the complete reconstruction of the northbound lanes. The work zone was situated north of Story City, Iowa on I-35, which was under construction. The northbound lanes were closed for about 6 miles and each of the two directions shared the I-35S (southbound roadway).

I-35N first became a single lane and then extended to the inner lane of I-35S. The camera, positioned to capture oncoming traffic, was placed about 50 ft downstream of the arrow board, where the right lane (of I-35N) began to merge into the left lane (of I-35N).

The southern site was also on I-35, starting at US 34 near Osceola, Iowa and ending at Decatur County. This road construction project also was a complete reconstruction.

3. DATA COLLECTION

Data were collected using a video monitoring trailer. The following sections of this chapter describe how we collected data for this project.

3.1 Equipment

The team had a mobile trailer with a telescoping pole that could be used to mount video cameras. They mounted two Autoscope cameras on a 30 ft pneumatically actuated boom as shown in Figure 3.1. The cameras were powered by four batteries capable of eight hours of operation. The resolution and optical zoom were set according to site location. The full color cameras were capable of 180 degree viewing and could be positioned to collect data in a specific area. The system was capable of monitoring traffic data for about one mile of a two- or four-lane roadway.

Figure 3.1. Trailer with boom partially collapsed

3.2 Site Configuration

Each time data were collected, a member of the team placed the trailer behind the arrow board, well away from moving traffic. The team placed the camera and conducted several test periods to determine the maximum extent of roadway that could be included in the camera view to provide the resolution needed to identify vehicle activity. (The camera could be zoomed out to view a very large roadway section, but a large viewing area corresponded to less detail for individual vehicles.) The viewing area was optimized to include as much roadway as possible while still retaining the ability to monitor individual vehicles. (The brightness and contrast on the photos in this report are enhanced.)

The study sections of value from the view of the camera were somewhat greater than 1,000 ft, so the team selected a 1,000 ft section for this study. Team members placed cones at 250, 500, 750, and 1,000 ft from the camera and defined the merging zones as shown in Figures 3.2 and 3.3.

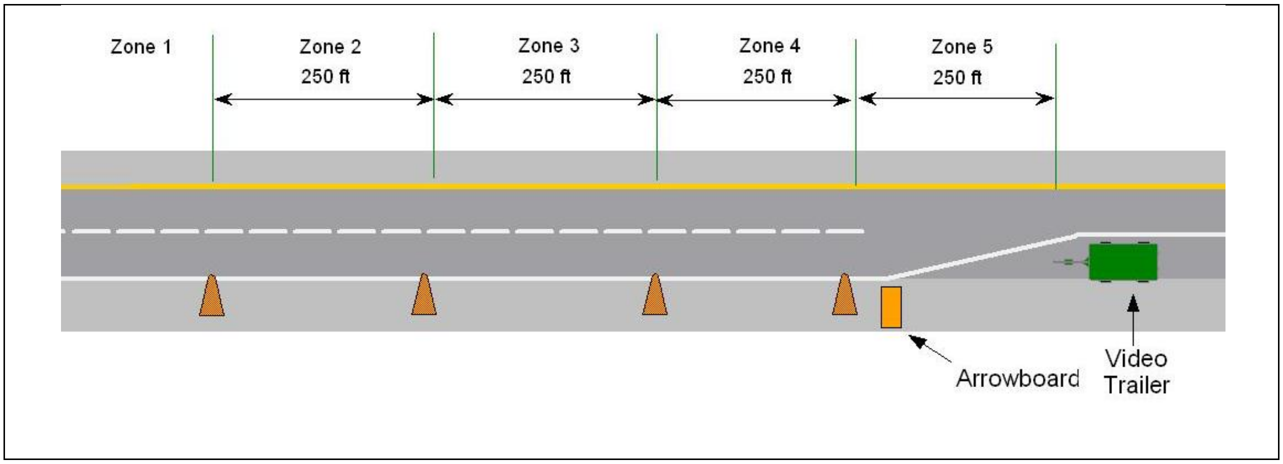


Figure 3.2. Location of zones (plan view)

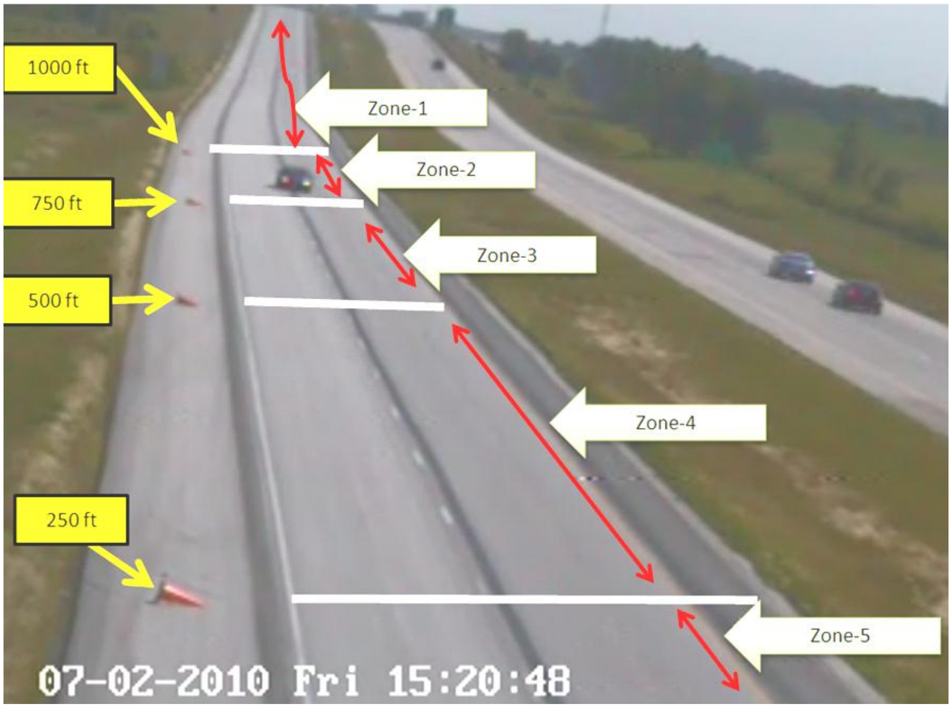


Figure 3.3. Location of zones (view from camera perspective)

Zone 1 is the road section 1,000 or more feet upstream of the video trailer. The road section from 1,000 to 750 ft is designated as Zone 2. Zone 3 and 4 were defined as 750 to 500 ft and 250 to 500 ft, respectively, from the video trailer. Zone 5 starts from 250 ft out and approaches toward the camera until the point where the right lane is no longer captured on video by the camera.

During each data collection period, team members placed the video trailer at the site as shown in Figure 3.2. The video trailer remained in place if data were collected over several days. The mast arm was raised only when video was actually being recorded and the team monitored the trailer. Although there was no reason to believe there would be a problem, the team didn't want to leave the mast arm up when not in use, in case of high winds or something unexpected.

The team collected data with two cameras for all data periods. One camera focused on the 0 to 1,000 ft area and the other provided a view of upstream traffic.

3.3 Data Collection Schedule

Given the intent of the project was to identify factors that lead to operational and safety problems, the team attempted to collect data during peak periods when queuing and breakdown were likely to occur. The cameras were typically set up long enough so that off -peak period data would also be collected to include free flow conditions.

The team determined that Thursday afternoon, Friday afternoon, and Saturdays would be the best data collection times. Data were collected as listed in Table 3.1. Attempts were made to collect data on a number of other days, but had to be canceled or shortened due to either high winds or thunderstorms. In addition, the cameras didn't have infrared capabilities, so the team couldn't collect data in dark conditions.

Data were collected for several days in May and it took some time for the team to finalize the data collection plan and camera set-up. As a result, the first three days of data collection at the northern site were not configured the same as later days of data collection, so the data from those first three days were not used in the analysis.

Data were also collected for one day at the Osceola I-35 site on June 11, 2010. At that site, data were collected at the south merge point of the northbound (NB) lane. This direction was selected because the team felt that higher volumes would be present in this direction. After the data were reviewed, they determined that lower volumes were present than expected. After a discussion with the Iowa DOT personnel in charge of the work zone, the team decided the Osceola I-35 site wasn't likely to result in queuing, except in rare circumstances. The team decided to focus on the I-35 site north of Story City.

At the Story City site, there was an entrance ramp about 1,000 ft upstream of the beginning of the tapered zone. This was likely to significantly affect the merge behavior upstream of the work zone, because more vehicles on the roadway were likely to already be in the left lane to give way to entering traffic from the ramp.

The team collected data as listed in Table 3.1. Data were also collected September 23, 2010, but the data were not included in the analysis. Data were scheduled to be collected for several additional days but canceled due to thunderstorms or high winds. In the end, six days of usable data were available for use in the analysis.

Table 3.1. Data collection times and notes

Date	Site	Data Collection Times	Notes
05/26/2010	I-35 near Story City	7 a.m. to 10 a.m.	Pilot study
05/27/2010	I-35 near Story City	7 a.m. to 10 a.m.	Pilot study
05/28/2010	I-35 near Story City	Morning and afternoon peak	Pilot study
06/11/2010	I-35 near Osceola	3 p.m. to 6 p.m.	Very low volume (served as a pilot study only)
06/24/2010	I-35 near Story City	3 p.m. to 7 p.m. (4 hours)	Dry pavement and normal operation
07/01/2010	I-35 near Story City	3 p.m. to 7 p.m. (4 hours)	Dry pavement and normal operation
07/02/2010	I-35 near Story City	3 p.m. to 7 p.m. (4 hours)	High congestion and aggressive actions by the drivers
08/05/2010	I-35 near Story City	3 p.m. to 7 p.m. (4 hours)	Dry pavement and normal operation
08/06/2010	I-35 near Story City	3 p.m. to 7 p.m. (4 hours)	Dry pavement and normal operation
09/23/2010	I-35 near Story City	3 p.m. to 7 p.m. (4 hours)	Bad weather (rain and wet pavement)
09/24/2010	I-35 near Story City	3 p.m. to 7 p.m. (4 hours)	Dry pavement and normal operation

4. DATA REDUCTION

A data reductionist reduced and recorded data for variables of interest from the video as described in the following sections. Table 4.1 provides definitions of data reduction terms and phrases and Figure 4.1 provides visual illustrations of them.

Table 4.1 Definitions of terms and phrases used in the data reduction

Accommodating driver/vehicle	A driver/vehicle in the open (left) lane, in front of a driver who is merging from the closing (right) lane to the open (left) lane; the accommodating driver may be impacted by the merging vehicle and the merging driver's ability to enter the open lane may be influenced by the accommodating driver's behavior
Begin taper	Point at which the roadway merge taper begins transitioning from two lanes to one lane
Conflict	When one or more driver's actions pose a safety risk without resulting in a crash
End taper	Point at which the merge taper ends, completing the transition from two lanes to one
Late merge	Driver of vehicle merges past the end taper
Lead vehicle	Vehicle in the open (left) lane, behind which another merging driver/vehicle enters the left lane
Merging driver/vehicle	A driver/vehicle that is merging from the closing (right) lane to the open (left) lane
Merge gap	Time or distance between the accommodating and lead vehicles
Post-merge gap	Time or distance between the accommodating and merging vehicle
Zone of influence	1,000 ft area upstream of the begin taper

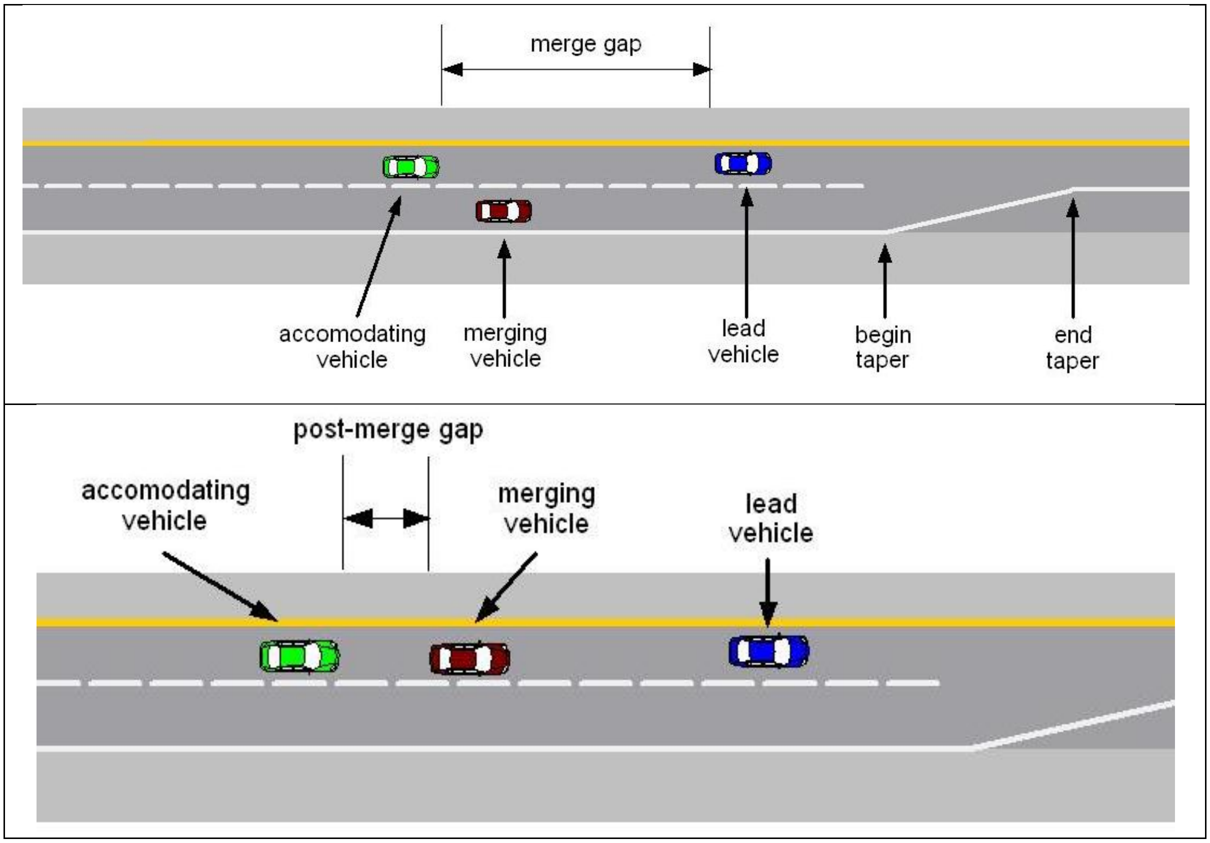


Figure 4.1. Illustration of data reduction terms

The data reductionist extracted variable data by viewing the video on a computer screen and manually coding the extracted information to a spreadsheet. The reductionist extracted data for multiple variables, including traffic volume and average speed, for each time period of interest. The data reductionist also coded each vehicle that merged within the study area as described below. During non-congested conditions, the reductionist reduced data using 15 minute intervals and during heavy congestion, the intervals were for every 5 minutes.

4.1 Volume and Vehicle Classification

The data reductionist collected volume data for each 5 or 15 minute interval using a manual count. The data reductionist actually counted the number of passenger vehicles and heavy trucks to compile this data.

4.2 Speed

The data reductionist extracted average speed for each corresponding 5 or 15 minute interval. For average speed data, the team identified a 500 ft interval using two of the 250 ft zones (Zones 3 and 4 from 250 ft to 750 ft upstream of the camera).

The researchers calculated speed by measuring the time a vehicle took to traverse the 500 ft interval. For each 15 minute interval, the team calculated speeds for 10 vehicles and for 5 minute intervals, they used as many vehicles as were available. Then, researchers calculated the average speed for each 5 or 15 minute interval.

The speed limit upstream of the work zone was 70 mph, with it reduced to 55 mph through the work zone itself (starting at the end point of the merge taper). Average speed varied from 30 to 60 mph, depending on the congestion level. The researchers also calculated the standard deviation for speed to quantify the speed variation within each 5 or 15 minute interval.

4.3 Merge Characteristics

The data reductionist recorded characteristics for each vehicle that merged within the 1,000 ft interval. The team recorded this information to help assess the quality of traffic operation in the work zone. The researchers used different characteristics to assess safety, as described in Section 4.4.

This study noted the location where each vehicle merged according to the zones shown in Figure 3.3. Vehicles merging in Zone 1 included vehicles that were already in the open (left) lane when reaching the 1,000 ft study area. Vehicles coded as merging in Zone 2, merged between 750 and 1,000 ft upstream of the end taper. Vehicles merging in Zone 3 merged between 500 and 750 ft upstream of the end taper. Vehicles merging in Zone 4 merged between 250 and 500 ft of the end taper. And, finally, vehicles merging in Zone 5 essentially merged within the last 250 ft of the taper area.

The data reductionist recorded the vehicle type for each merging vehicle according to the conventions in Table 4.2.

Table 4.2. Vehicle classification

Vehicle Type	Coding Convention
Motorcycle	M
Passenger car (with or without trailer)	P (or PT)
SUV and pickup (with or without trailer)	SP (or SUVT, PUT)
Six type single unit	SS
RV	RV (BRV, PRV)
Bus (interstate, long distance)	B
Single unit truck	T1
Multi-unit truck	T2
Construction truck	T3
Semi with additional lengths	T4
Wide load truck	T5

Vehicle merge behavior was assessed and coded according to the following. Merge behavior indicates how successfully a vehicle merged into the open (left lane) of traffic. How a merging vehicle influences traffic depends on the actions and characteristics of the merging and accommodating drivers.

Merging driver behavior dictates gap size and merging transition. Merging drivers who make a smooth transition with an adequate gap cause little influence on upstream traffic. Merging drivers who take smaller gaps, make erratic lane changes, or force merges may affect upstream traffic by causing braking, slowing, and even swerving.

The tolerance of accommodating drivers is also a factor. Accommodating drivers perceive the post-merge gap or merging behavior differently. Drivers who are less comfortable with the post-merge gap size or erratic movements of merging drivers, may brake or slow, which impacts upstream traffic differently than accommodating drivers who react in a less defensive manner.

The team defined a set of metrics to qualitatively assign to driver merge behavior. The metrics were based on descriptions and definitions of merge behavior defined by Heaslip (2007). Accommodating vehicle behavior was qualitatively assessed by whether the vehicle visibly appeared to brake, slow, or swerve or whether the gap was small enough that some action would need to be taken on the part of the accommodating driver. Table 4.3 defines the metrics used for this study.

Table 4.3. Description of merge types

Metric	Description
No Impact	Accommodating driver/vehicle was unaffected by the behavior of the merging driver/vehicle
Forced Merge	Accommodating driver/vehicle visibly slowed or gap size was small enough that accommodating driver was likely to have taken some action
Late Merge	Merging driver accomplished the merge within 0 to 250 of the merge point and accommodating driver was unaffected by the merging behavior of the merging driver/vehicle
Late Forced Merge	Merging driver accomplished the merge within 0 to 250 of the merge point and the accommodating driver/vehicle visibly slowed or gap size was small enough that the accommodating driver was likely to have taken some action

The photos in Figures 4.2 through 4.5 help illustrate the merge types in Table 4.3.

Figure 4.2 shows a vehicle merging with a very large gap and Figure 4.3 shows a merge with an adequate amount of room. Both were classified as no impact.

Figure 4.2. Vehicle merging with large gap

Figure 4.3 shows a vehicle merging with a small gap, but no noticeable reactive behavior by the accommodating driver/vehicle and an adequate gap size. Again, this was classified as no impact.

Figure 4.3. Vehicle merging with adequate gap

Figure 4.4 shows a vehicle merging with a small gap, which was classified as a forced merge.

Figure 4.4. Vehicle merging with small gap

Figure 4.5 shows a late forced merge by a large truck. The gap was so small that the accommodating driver would have had to brake to accommodate the truck.

Figure 4.5. Tractor semi trailer forcing merge

5. EVALUATION OF BEHAVIORS IMPACTING WORK ZONE TRAFFIC OPERATION

Merge behavior was expected to have the most impact on work operations. During the course of the data reduction, several other behaviors were noted that may also impact traffic flow and operations in a work zone. A qualitative assessment of the impact of those behaviors is discussed in section 5.1.

A quantitative assessment of the impact of merge behavior was conducted, as described in section 5.2, using a time series analysis and logistic regression.

5.1 Analysis of Behaviors Impacting Work Zone Traffic Operations

Two driver merge behaviors that were likely to contribute to breakdown of traffic flow and operations were forced merges and late merges. Other driver behaviors that are likely to affect traffic flow and operations were identified during the course of reviewing the video for merge behaviors. Behaviors that were identified as having an impact on traffic flow and operations are discussed in the following paragraphs.

5.1.1 Description of Behaviors

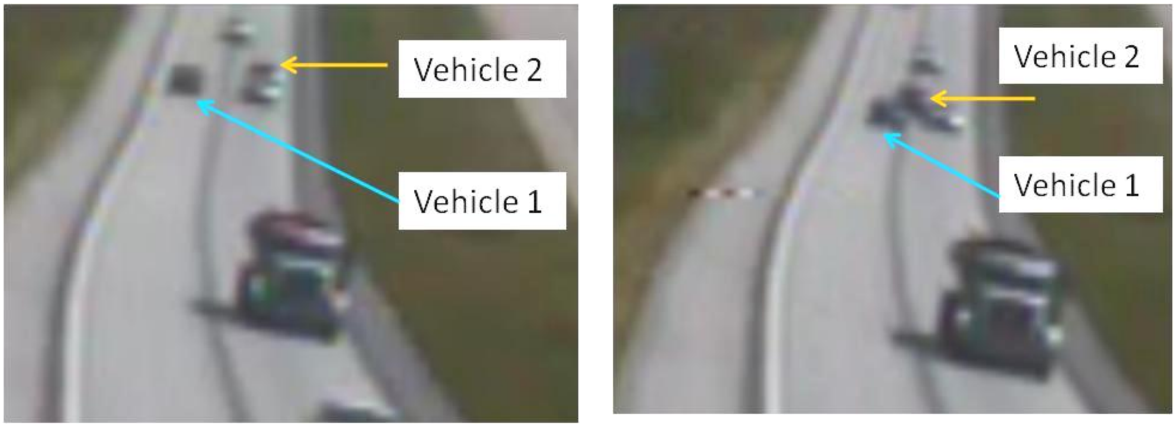
The following describes other behaviors that are likely to impact work zone operations.

Forced Merge: A forced merge occurs when a merging driver takes a gap that is too small to accommodate their vehicle causing the accommodating driver to slow or take some action to avoid a conflict.

Late Merge: A late merge occurs when the merging driver accomplishes the merge within 0 to 250 ft of the merge point.

Queue jumping: Queue jumping occurs when a driver already in the open lane decides to jockey for a better position by moving to the closing lane and passes one or more vehicles before merging back into the open lame. Queue jumping was only recorded when it was within the camera’s field of view and this may have occurred outside of the 1,000 ft study area, but was only reported as an operational problem if the driver merged back into the open lane within the 1,000 ft interval.

Queue jumping is expected to affect traffic operations for several reasons. First, drivers who queue jumped (but not recorded) just upstream of the 1,000 ft study area also frequently had to merge within the 1,000 ft interval, which was likely to result in a forced merge. Forced merges can have a significant impact on traffic operations because accommodating drivers are forced to slow and, in some cases, even brake.

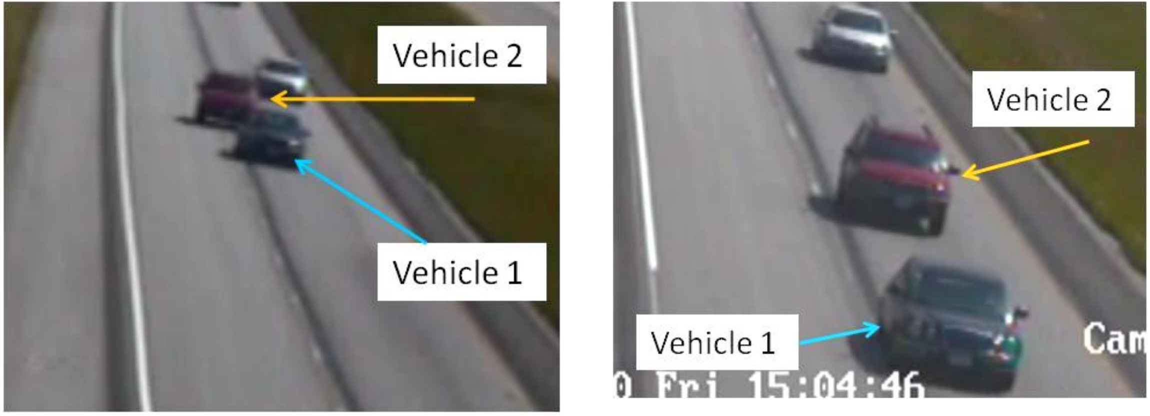


Vehicle 2 in open lane and vehicle 1 attempting to merge well upstream

Vehicle 2 begins moving into closing lane

Vehicle 2 begins passing vehicle 1

Vehicle 1 lane straddles to prevent vehicle 2 from passing



Vehicle 1 still straddling to prevent vehicle 2 from merging

Vehicle 2 finally does late merge

Figure 5.1. Example of queue jumping resulting in aggressive behavior

Second, drivers may realize that they are not able to move any farther up in the queue and return to their original position. The vehicle immediately behind the queue jumper may still have to slow or brake as the queue jumper returns to their original position.

Third, queue jumping appeared to evoke aggressive behavior by other drivers who likely felt that everyone should “take their turn” in line. This may be manifested by lane straddling, which is described below. An example is shown in Figure 5.1.

As illustrated, driver/vehicle 1 attempts to queue jump well in advance of the 1,000 ft study area. Driver/vehicle 2 merges and then realizes that driver/vehicle 1 is attempting to queue jump. Driver/vehicle 2 lane straddles and forces driver/vehicle 1 to jockey for position until almost the begin taper. In this situation, a late merge occurred that might not have if driver/vehicle 1 had stayed in their lane or driver/vehicle 2 had not reacted aggressively.

Figure 5.2 illustrates queue jumping with the study interval. As shown, the blue vehicle queue jumps within the 750 to 1000 ft zone, then attempts go around the red semi. The blue vehicle then cuts in front of the semi at the begin of taper.

Blue vehicle queue jumps upstream

Blue vehicle cuts in front of semi near begin taper

Figure 5.2. Queue jumping vehicle cuts in

Lane straddling: Lane straddling is when a driver intentionally places their vehicle across portions of both the open and closing lane to prevent drivers/vehicles behind them from passing and merging ahead of them, as shown in Figures 5.3 and 5.4.

The team noted that lane straddling impacted forced and late merges. Drivers who were following lane-straddling drivers upstream of the 1,000 ft study area often were not able to merge until they reached the study area. It is not known, however, if those same drivers would have merged sooner had they not been blocked by lane straddlers. Lane straddling was only observed when congestion occurred.

Figure 5.3. Two semis lane straddle, preventing other vehicles from passing

Figure 5.4. Passenger vehicle lane straddles, blocking two vehicles upstream

5.1.2 Qualitative Assessment of Behaviors

Table 5.1 summarizes late and forced merges by the behavior preceding the merge.

Table 5.1. Summary of merge events

Event	**Forced Merge**	**Late Merge**	**Late Forced Merge**
Queue Jump	4	7	4
Lane Straddle	1	2	13
Regular	13	52	21
Total merges	**18**	**61**	**38**

The first row shows forced, late, or late forced merges, which were a result of queue jumping. The second row shows events that were a result of lane straddling. And, the third row shows regular merges where no queue jumping or lane straddling occurred. A late forced merge is not counted again as either a late merge or a forced merged.

As indicated, 22.2 percent of forced merges, 11.5 percent of late merges, and 10.5 percent of late forced merges occurred with queue jumping. Lane straddling occurred for 5.6 percent of force merges, 3.3 percent of late merges, and 34.2 percent of late forced merges.

Table 5.2 summarizes queue jumping events and the impact of each event. Drivers who queue jumped typically only passed one driver/vehicle, which did not noticeably improve their position in the queue.

Table 5.2. Summary of queue jumping

	Queue Jumps	**Vehicles Passed**	**Forced Merges**	**Late Merge**	**Late Forced Merge**
Total	30	32	4	8	4

During the analysis period, 30 drivers/vehicles queue jumped, resulting in 4 forced merges (13.3 percent), 8 late merges (26.7 percent), and 4 late forced merges (13.3 percent) for a total of 16 merge impacts. Late forced merges were counted separately from late merges or forced merges. To reiterate, although drivers who queue jumped did not significantly improve their vehicle position, they had a large impact on surrounding traffic.

Table 5.3 provides a summary of lane straddling events. As shown, lane straddling occurred in 51 instances during data collection.

Table 5.3. Summary of lane straddling

	Vehicles Engaged in Straddling (#)	Straddling Instances	Forced Merge	Late Merge	Late Forced Merge
Total	71	51	1	2	14

When lane straddling occurred, 28.6 percent of the time, more than one vehicle engaged in lane straddling, resulting in 71 vehicles engaging in lane straddling. Lane straddling incidents occurred 51 times and resulted in 1 forced merge (2.0 percent), 2 late merges (3.9 percent), and 14 late forced merges (27.5 percent) for a total of 17 resulting incidents. Late forced merges were counted separately from late merges or forced merges. Although it cannot be fully quantified, lane straddling did not appear to impact traffic operations as much as queue jumping.

In some cases, lane straddling vehicles appeared to slow traffic upstream as they blocked the lane. This usually occurred with large trucks. When this occurred, it appeared as though the lane-straddling vehicle driver slowed to just stay just ahead the vehicle that was originally just upstream of them in the open lane. As the lane-straddling vehicle driver attempted to keep pace, they slowed enough that large gaps appeared in the traffic stream ahead of them, even though significant congestion was present upstream. This is shown in Figure 5.5.

Figure 5.5. Lane-straddling vehicle driver creates large gap attempting to stay even with upstream vehicle to prevent passing

5.2 Analysis of Merge Behavior

A statistical analysis of the impact of aggressive behavior using two different analyses. The first attempted to determine with late and forced merges, which were more likely to occur. The second attempted to quantify the behavior of late and forced merges on traffic operations.

5.2.1 Analysis of When Late and Forced Merges Occur

Average speed, volume, vehicle type, and merge type (late merge, forced merge, and late forced merge) were extracted from the videos in 15 minute intervals, as described in Section 4. Table 5.4 defines the variables used.

Table 5.4. Variables used in logistic regression analysis

Variable	Description	Variable Type
QV	Average volume for 15 minute interval	Continuous
QAS	Average speed for 15 minute interval	Continuous
QSS	Standard deviation of speed for 15 minute interval	Continuous
TP	Percentage of heavy trucks for 15 minute interval	Continuous
TM	Total merges occurring from 0 to 1,000 ft from the video trailer	Continuous
LM	Total late merges (0 to 250 ft)	Binary
FM	Total forced merges (0 to 1,000 ft)	Binary

Logistic regression was used to assess the probability of a late or forced merge. Correlation between variables was assessed and correlation coefficients among variables are provided in Table 5.5.

Table 5.5. Correlation table

	LM	FM	QV	QAS	QSS	TP
LM	1.00					
FM	0.39	1.00				
QV	0.20	0.44	1.00			
QAS	-0.17	-0.62	-0.34	1.00		
QSS	0.06	0.26	0.19	-0.28	1.00	
TP	-0.10	-0.23	-0.43	0.26	-0.18	1.00

To assess the effect of traffic on merging behavior, the response variables were transformed to binary ones:

- Late merge binary (LMB)
- Forced merge binary (FMB)

This was done to make these categories:

- Late merge versus early merge
- Forced merge versus normal merge

Logit regression is a statistical model used for predicting the probability of occurrence of an event with binary outcomes by fitting the data to a logit function logistic curve. A logistic function is given by the following equations:

$$f(y) = \frac{1}{1+e^{-y}} \tag{5.1}$$

where:

$$y = \beta_0 + \beta_1 * x_1 + \beta_2 * x_2 + \ldots \tag{5.2}$$

Here, $f(y)$ is the probability density logistic function and y is the response, which is modeled using linear regression of the given covariates (independent variables). In general, this method is used for modeling discrete choice responses, such as route choice, transportation mode choice, and many other transportation-related categorical variables. This method can be extended to more responses with more than one choice. In our analysis, y signifies LMB and FMB.

Logistic regression was run on data with LMB and FMB as response variables and QV, QAS, QSS, and TP as explanatory variables using the statistics software R (version 2.12.0). Model selection was done based on Akaike Information Criterion (AIC) while ensuring that all the covariates in the model were significant. In this section, only the final models with significant covariates are shown.

The final model, which assesses likelihood of a late merge versus an early merge occurring is given by:

$$f(\mathrm{LMB}) = \frac{1}{1+\exp(-\mathrm{LMB})} = \frac{\exp(\mathrm{LMB})}{\exp(\mathrm{LMB})+1} \tag{5.3}$$

where:

$$\mathrm{LMB} = 0.0045 * \mathrm{QV}\ (\pm 0.001) \tag{5.4}$$

LMB is the binary transformation of LM. QAS is significant at 95 percent level of confidence.

Results indicate that for every unit increase in quarterly volume, the log odds of merging late increases by about 0.0045. The implication is that as volume increases, the gaps in the traffic would be narrower and, therefore, the driver is more likely to merge late. Figure 5.6 shows the probability plot for different values of traffic volume. So, if we increase volume by 1 vehicle, the log odds of merging late increases by 0.0045.

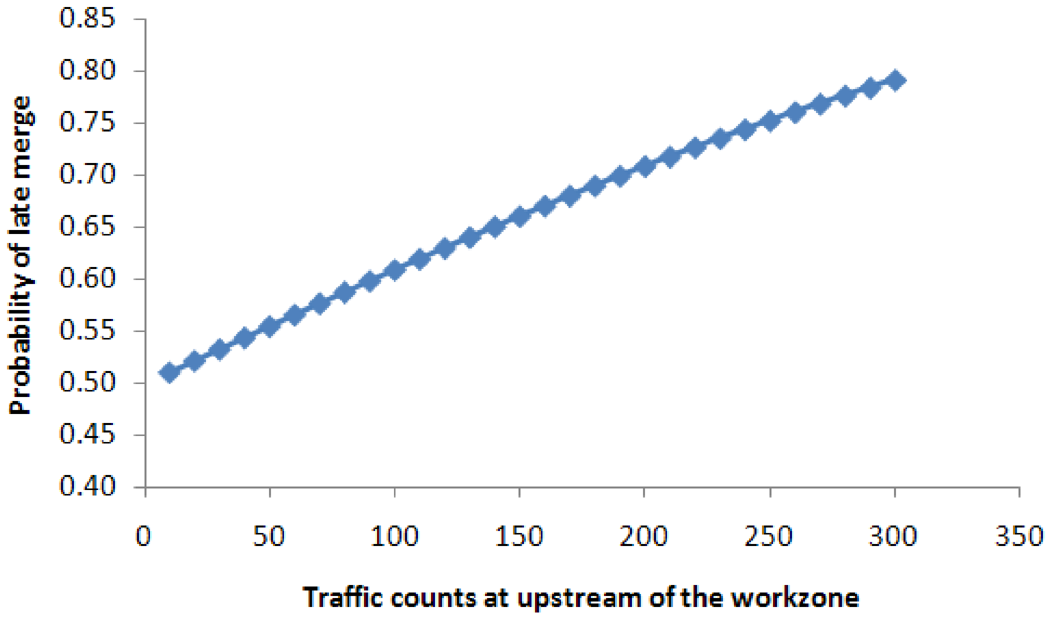


Figure 5.6. Predicted probability of late merge for different traffic volumes

The final model that assesses the probability of a forced merge occurring is given by:

$$f(\mathrm{FMB}) = \frac{1}{1+\exp(-\mathrm{FMB})} = \frac{\exp(\mathrm{FMB})}{\exp(\mathrm{FMB})+1}, \quad (5.5)$$

where:

$$\mathrm{FMB} = 0.018{*}\mathrm{QV}\ (\pm 0.0048)\ -0.078{*}\mathrm{QAS}\ (\pm 0.020) \quad (5.6)$$

Both QV and QAS are significant at 95 percent level of confidence.

Results indicate that the log odds of forced merge (versus not a forced merge) increases by 0.018 for each unit increase in quarterly traffic volume. Similarly, a unit increase in quarterly average speed would decrease the log odds of forced merge by 0.078. This indicates the probability of a forced merge increases at volume increases and decreases as speed increases. This is exactly as one would expect, because when volumes are low and speeds are high, large gaps are present, which facilitate normal merges. And, when the opposite is true, gaps are smaller, which may result in more forced merges. Figure 5.7 shows the probability plot for forced merges at mean traffic volume.

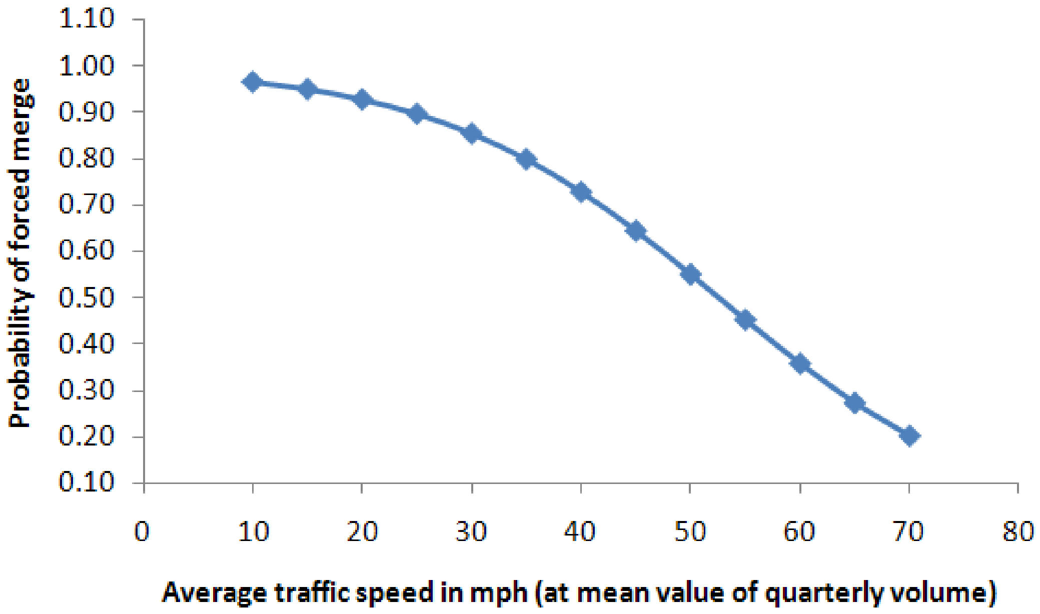


Figure 5.7. Predictive probability of forced merge for different speed at mean traffic volume

5.2.2 Analysis of the Impact of Forced Merges on Upstream Traffic Operations

A time series analysis was used to model the impact of merging behavior on upstream work zone operations. Time series analyses are able to model the impact of one variable in one time period on other variables in a subsequent time period. For instance, the impact of a forced merge in time period t on speeds in time period $t + \Delta t$ can be assessed.

Average speed was the response variable used as a surrogate for traffic operation. Volume and speed were highly correlated given that volume was collected within the 1,000 ft zone before the end taper. Consequently as traffic slowed, volume decreased. Speed was selected rather than volume because volume can also be low when demand is low but, in that case, speeds are high. The difference between traffic volume and upstream demand would likely have been a better indicator of traffic operations, but it wasn't possible to collect upstream volume to obtain demand.

During time of low demand, the impact of aggressive driving on upstream traffic, in general, is restricted to few minutes. In a time series analysis it is also not appropriate to combine data from different days. Consequently, it was decided to use data from one day when significant queuing and aggressive driving was present over a significant period. Data from July 2, 2010 was selected. Data had originally been reduced by 15 minute intervals but it was decided to evaluate the data in 5 minute intervals since it would be difficult to pinpoint the immediate impact of negative behaviors over a large intervals. Speed, volume, and standard deviation of speed were measured for 5 minute intervals.

Average speed was found to have serial correlation (meaning speed was correlated with its lag terms). This is because the observations were separated by an equal interval of time (five minutes). Observations taken at equal time intervals tend to posses serial correlation. A time series model is appropriate for such data. A time series model exploits autocorrelation in data and models the response with its own lagged terms and other covariates.

The form of the model is given by:

$$Y_t = \beta_0 + \beta_1 * Y_{(t-1)} + \beta_2 * Y_{(t-2)} + \beta_3 * Y_{(t-3)} + \ldots + \varepsilon \qquad (5.7)$$

where:

ε = the error term which is assumed to take care of all dependent variables and uncertainties
t = time

Several models were developed and the best fit model was selected.

$$\text{Avgspeed}_t = -0.50 * \text{Avgspeed}_{(t-1)}[\pm 0.12] + \varepsilon \qquad (5.8)$$

The mean square absolute error (MSAE) and root mean square error (RMSE) were found to be 0.20 and 0.08, respectively, for this model.

Several models were developed which tested the impact of different explanatory variables on the response variable. In Figure 5.8, observed average speed is shown on the left or y axis and number of forced merges (binary transform) is shown on the right. As indicated, average speed data are correlated and decrease as soon as vehicles started doing forced merges. This information was used to improve upon the previous model.

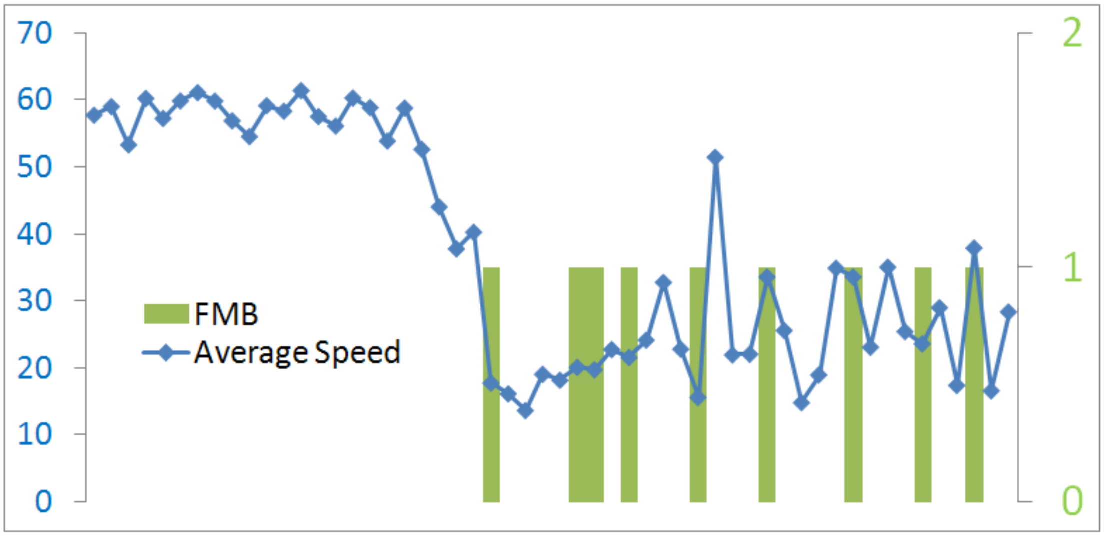


Figure 5.8. Observed average speed and forced merge events (1 for forced merge binary/FMB, 0 for normal merge or no-merge)

The situation is what is called intervention in time series analysis and is handled through intervention or interrupted time series models. We assume, in this case, that the beginning of forced merge events (around 4:40 p.m.) is an intervention that persisted until the end of the data collection period for the day. We can also assume that forced merge is a step function with Figure 5.9 approximating the one shown in Figure 5.8. In this case, two different series exist: one before the intervention and one after it. Time series models for both the series were developed and it was found that both of them were approximately similar, except there was a downward shift in the average speed. The average speed decreased from 55 mph to 24 mph.

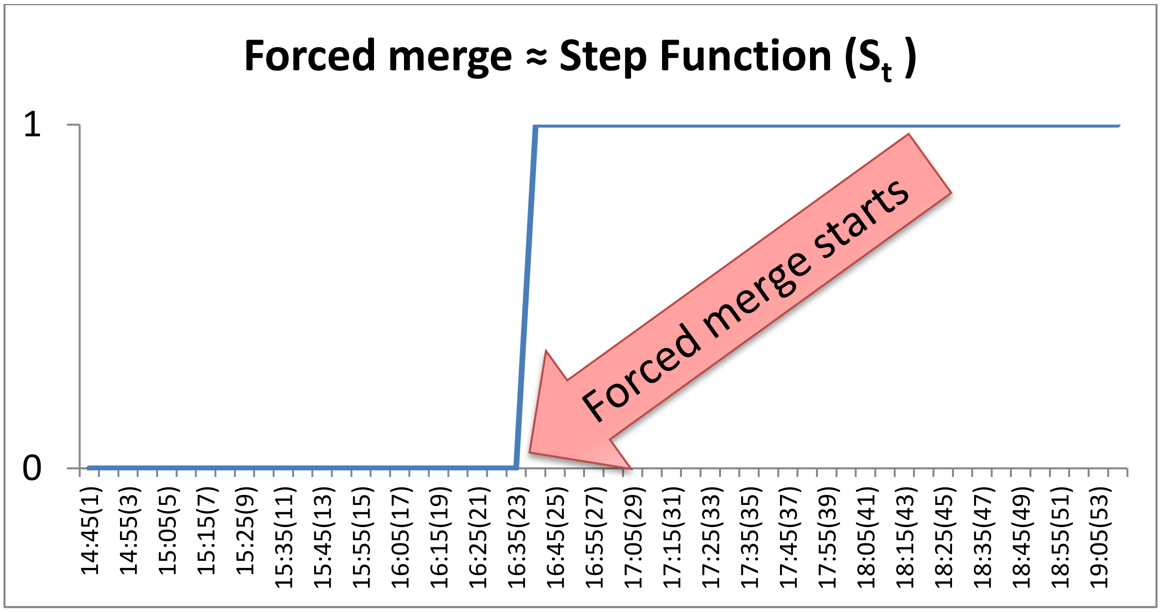


Figure 5.9. Step function approximating forced merge events

The model can be described as, let the original series before intervention be:

$$N_t. \tag{5.9}$$

and, the time series with intervention be:

$$N_t + S_t \tag{5.10}$$

where:

$S_t = 1$ for time $\geq$4:40 p.m.

otherwise:

$S_t = 0$ (as shown in Figure 5.9.)

A time series model that assumes forced-merges to be the cause of disruption in speed was developed. The outliers were also incorporated in the model.

$$\text{Avgspeed}_t = -0.60*\text{Avgspeed}_{(t-1)}[\pm 0.12]+0.86*(\text{Outlier-37})[\pm 0.18]+0.57*(\text{Outlier-44})[\pm 0.18]-0.83*(\text{Intervention-ForcedMerge})[\pm 0.19] + \varepsilon \tag{5.11}$$

or:

$$\text{Avgspeed}_t = -0.60*\text{Avgspeed}_{(t-1)}+0.86*(\text{Outlier-37}) +0.57*(\text{Outlier-44})-0.83*(\text{Intervention-ForcedMerge}) + \varepsilon \tag{5.12}$$

The MSAE and RMSE decreased to 0.18 and 0.067, respectively. Figure 5.10 depicts how the two models characterize true observations. The significance of the forced merged variable in the intervention model supports the hypothesis that speed decreased due to force merge events.

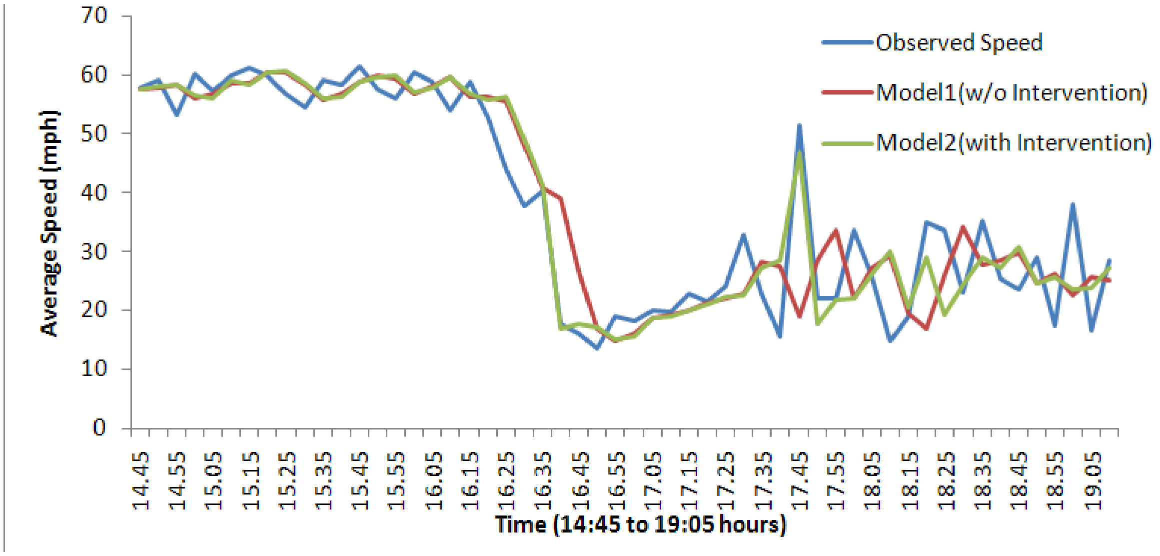


Figure 5.10. Observed average speed and values obtained from the model

Figure 5.10 shows how the intervention model (Model 2) captures the observed average speed better than the simple time series model (Model 1). The developed time series model can be used to forecast traffic operation after the forced merges. One important thing that can be seen from Figure 5.10 is that the standard deviation in speed increases (6.43 to 8.33) after the forced merges occur.

A limitation of the analysis is that the data set is small and speed was averaged over entire five minute duration which was assumed to be short. However, within five minutes a number of events can occur disrupting the average speed time series further.

6. EVALUATION OF BEHAVIORS IMPACTING WORK ZONE TRAFFIC SAFETY

Since crashes are rare events, it is not unexpected that no actual crashes were recorded during the study. However, the video data were used to record behaviors that could compromise safety (even though the rare event of a crash wasn't actually recorded during the study). The following sections further describe the observed behaviors that pose a potential safety risk.

In particular, a number of aggressive behaviors, which are not likely to occur during normal traffic operations on rural freeways or expressways, were manifested in the work zone. Drivers appeared most likely to engage in these behaviors when congestion was high entering the work zone.

Behaviors, which may compromise safety, that were noted in the course of evaluating work zone video are summarized in the following sections. It was not possible to quantify the safety risk, so this information is a subjective assessment of behaviors that pose some safety risk.

6.1 Forced merge

Chapter 4 provides a description of forced merges. A forced merge was considered in all instances as posing a safety risk, given the potential for a crash is high if the accommodating driver does not take some action. Forced merges may require some slowing by the accommodating driver and may result in hard braking, swerving, or other evasive maneuvers by the accommodating driver as gap size decreases. Figure 6.1 shows a vehicle forcing a merge into a very small gap.

Figure 6.1. Tight forced merge

6.2 Queue jumping

Chapter 5 describes queue jumping. Queue jumping causes a safety risk because, in many cases, queue-jumping drivers speed up to get around the vehicles they are passing. Drivers who queue jumped just upstream of the 1,000 ft study area also frequently had to merge within the 1,000 ft interval, rather than before it, and was also likely to result in a forced merge. Surrounding drivers often reacted aggressively to queue-jumping drivers by lane straddling and attempting to block queue jumpers from merging back into the open lane. As shown in Table 5.2, 30 vehicles queue jumped, resulting in 8 forced or late forced merges, which are a safety issue.

6.3 Lane straddling

Chapter 5 describes lane straddling. (Lane straddling occurs when a driver already in the open lane moves out of the center of their lane and straddles the centerline. This behavior blocks drivers upstream in the closing lane from merging past the lane straddling driver.) Lane straddling is a safety issue because it may result in forced merges by drivers that are behind the straddling vehicle. As shown in Table 5.3, 17 of the 51 lane straddling incidents (33.3 percent) resulted in a late or late forced merge. Lane straddling also resulted in several other safety-compromising behaviors as listed in Table 6.1.

Table 6.1 Safety-compromising behaviors observed as a result of lane straddling

Instances	Observed Behavior
4	Following driver/vehicle using shoulder to pass lane-straddling vehicle (see Figure 6.2)
2	Drivers/vehicles appear to fight for space to merge
1	Following driver/vehicle cuts into space that lane-straddling driver/vehicle leaves partially unoccupied
2	Following and lane-straddling vehicle drive two-abreast for some distance (see Figure 6.3), and, in one of these cases, vehicles race abreast until arrow board, where forced merge occurs

Figure 6.2. Lane straddling results in drivers passing on shoulder

Figure 6.3. Lane straddling results in vehicles driving two-abreast

6.4 U-Turns in Median

In a number of instances, vehicles turned around in the grass median, as shown in Figure 6.4. This creates an unsafe situation as drivers attempt to pull out of the median and into the lanes of traffic in the opposite direction. This is particularly problematic because opposite-direction drivers are not expecting the maneuver. During the course of the study, 7 vehicles turned around in the median, and each instance was usually during a highly-congested period. 2 construction vehicles and 1 police officer also turned around in the median.

Figure 6.4. Vehicles turning around in the median

Several other safety-compromising behaviors occurred. In one instance, a merging driver/vehicle merged in the area occupied by a motorcycle. It is unknown if the driver didn't see the motorcycle or was intentionally attempting to share the space. In another situation, 2 vehicles pulled onto the left shoulder and used the shoulder to pass other vehicles as shown in Figure 6.5.

Figure 6.5. Vehicle passing on left shoulder

6.5 Speeding

Within a work zone, speeding is problem because of the danger it poses to on-road workers. At the merge point, speeding is a problem for several reasons. First, merges may be more difficult at high speeds. Next high speed differentials can be created when some drivers slow to work zone speeds and others maintain freeway speeds. The mix of merging vehicles and high speed differentials poses a safety risk. Finally, the potential for conflict is higher when forced merges occur and the accommodating driver is traveling at high speeds and has less time to react. When crashes do occur, higher speeds are likely to result in more severe outcomes.

Speeds within the work zone were not examined given the focus of this study was traffic and operations at the merge point. Speeds at in 1,000 ft section upstream of the merge point were used to determine the extent to which speeding was a problem. The posted speed limit on I-35 is 70 mph during normal operations.

Upstream of the work zone, the posted speed for the work zone was 55 mph. Average speeds for the 5 minute or 15 minute intervals for the six analysis days and compared the mean speed to the 55 mph speed limit posted for entering the work zone.

Average speeds were based on a sample of 10 vehicles (or as many as were available during 5 minute intervals), as described in section 4.2. The 85th percentile speed may have been a better metric. However, it is difficult to calculate 85th percentile speed with any confidence with only 10 vehicles. As a result, average speed was the metric used.

A total of 84 intervals, 15 minutes long, were available for the six study days. This included July 2, 2010, where significant congestion was present and speeds were depressed. As shown in Table 6.2, the mean speed was greater than 55 mph for 49 of the 84 intervals. Consequently, the mean speed was above the posted speed limit 58.3 percent of the time.

Table 6.2 Speed metrics

Including 15 Minute Intervals for All Study Days		
Mean Speed	**Intervals (#)**	**Percentage**
Mean speed > 55 mph	49	58.3 percent
Mean speed ≥ 60 mph	33	39.3 percent
Mean speed ≥ 65 mph	6	7.1 percent
Excluding 15 Minute Intervals when Congestion Occurred		
Mean Speed	**Intervals (#)**	**Percentage**
Mean speed > 55 mph	46	74.2 percent
Mean speed ≥ 60 mph	31	50.0 percent
Mean speed ≥ 65 mph	6	9.7 percent

When congested periods were not included in the analysis, mean speeds were greater than the posted speed limit for 46 of the 62 fifteen-minute intervals (74.2 percent), also shown in Table 6.2. Mean speeds were 5 mph over the posted speed limit 50.0 percent of the time and mean speeds exceeded the posted speed limit by 10 or more mph a total of 9.7 percent of the time.

7. IDENTIFICATION OF STRATEGIES

A number of strategies have been suggested to improve work zone operations, as discussed in this Chapter. Several of the strategies aim to improve merging behavior, as discussed below in sections 7.1 and 7.2. Measures to reduce speeding are also included in section 7.3.

7.1 Automated Work Zone Information Systems

Some areas have used Automated Work Zone Information Systems (AWIS) to improve work zone operations. AWIS provide useful real-time traffic information to motorists approaching or passing through a work zone. Most systems combine traffic sensors and changeable message signs (CMSs).

The CMSs are programmed to display the appropriate message based on traffic conditions. Chu et al. (2005) evaluated AWIS in a work zone on freeway I-5 NB in Santa Clarita, California. The system had several CMSs, which displayed different messages depending on traffic conditions. A sample of the messages included: Traffic Jammed to Magic Mountain/Expect 15 Min Delay and Slow/traffic/ahead – prepare to stop.

Chu et al. (2005) found that speeds improved slightly at one site and were essentially the same at the second, while speed variance decreased significantly from the before to after period at both sites where speed was evaluated. They also found that the signing was effective in diverting traffic to alternate routes. Results of a driver survey also indicated that drivers felt that the system was useful in providing information about the delay and alternate routes.

7.2 Late Merge Signing

The late merge signing concept was used by some agencies to improve work zone flow. With this approach, signing instructs drivers to continue using all available traffic lanes until they reach the work zone taper. Signs also instruct drivers to take turns merging just before they reach the begin taper (See Figure 7.1).. The concept is that capacity increases by using all of the roadway space up to the work zone taper (Beacher et al. 2005).

The strategy was developed by the Pennsylvania DOT (PennDOT) in attempt to reduce aggressive driving at merge points. The signing consists of static Use Both Lanes to Merge signs placed 1.5 miles upstream of the merge point and static Merge Here Take Your Turn signs as shown in Figure 7.1. Both signs are placed on both sides of the roadway (Beacher et al. 2005 and McCoy et al. 1999).

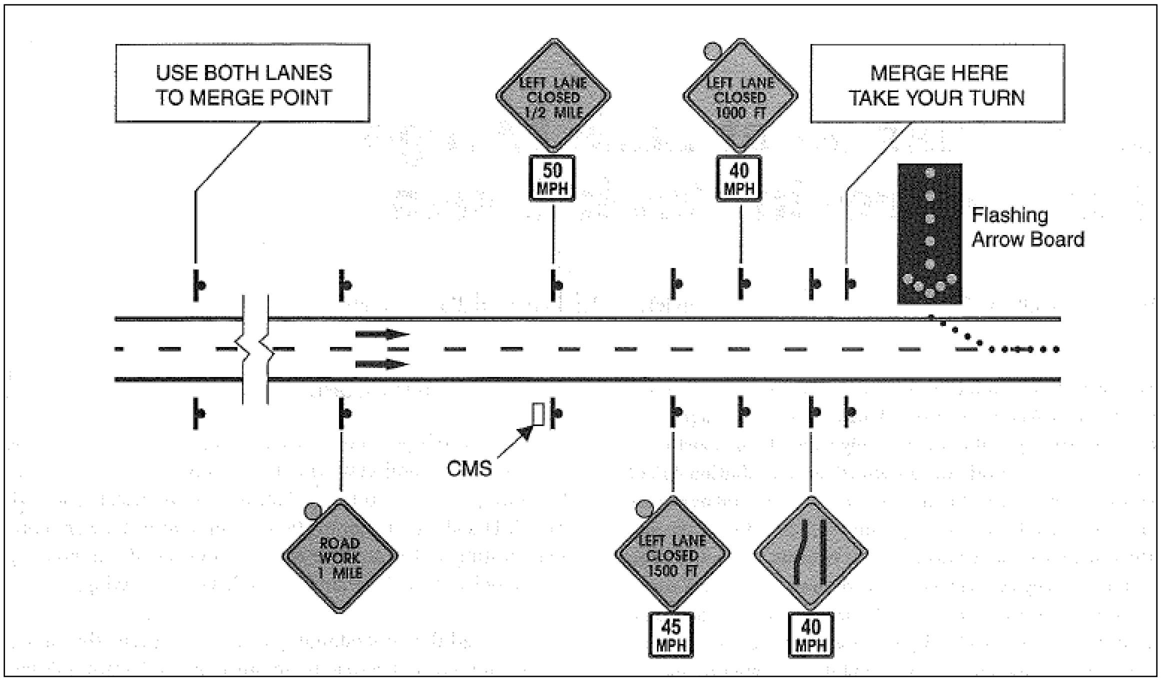


Figure 7.1. Diagram of late merge signing (Beacher et al. 2005)

The strategy was evaluated in three different studies. The University of Nebraska conducted a study in Pennsylvania at a two-to-one-lane-reduction scenario. They collected data using video cameras and Light Detection And Ranging (LIDAR) speed guns over four days. They reported that work zone capacity increased by about 1,470 vehicles per hour and late merges were reduced by 75 percent.

The researchers found that the benefits were most pronounced when heavy congestion was present. They cautioned that effective signing is important to restructure driver expectation. They also reported it was more difficult for large trucks to merge left to right than right to left.

The Texas Transportation Institute (TTI) conducted a field evaluation of the late merge signing strategy in a three-to-two-lane work zone closure. They collected data for one day using cameras and field data collection personnel who monitored queue length. The researchers estimated that the late merge signing delayed the onset of congestion by 14 minutes. They also reported that the queue length was reduced from 7,800 to 6,000 ft, but indicated this may have been due to early removal of the lane closure or changes in demand. They also reported that a larger percentage of vehicles used the open lane with the late merge signing and higher capacity occurred at the merge point (Walter and Cooper 2001).

Beacher et al. (2005) also conducted a field evaluation of the late merge signing at one work zone site. The team consulted with the Virginia DOT (VDOT) and made site visits to rank potential sites according their suitability for project objectives. The site was a two-to-one-lane closure at a site 0.5 miles south of the downtown area of Tappahannock, Virginia.

The speed limit on the section with the work zone was 45 mph, which was reduced to 35 mph at about 200 ft before the arrow board. Speeds were further reduced to 25 mph about 1,000 ft past the taper.

The researchers collected volume data using traffic counters and temporary loop detectors, which were placed about 5,500 ft from the start of the taper (begin taper), 2,000 ft from the start of the taper, and just past the merge point (end taper). The researchers collected data only during heavy congestion periods. They collected queue length and travel time using two probe vehicles during peak hours. Each probe vehicle traveled in the open lane without changing lanes. As approaching the end of the queue (merge point), they recorded the distance and time to arrow board.

Both a standard Manual of Uniform Traffic Control Devices (MUTCD) work zone traffic control plan (TCP) and a late merge signing TCP were tested at the site. The researchers modeled the late merge signing TCP on the Pennsylvania model, but, after consulting with a panel that included VDOT and Virginia State Police personnel, they changed the first message to: Stay in Lane to Merge Point.

Stepwise regression models were developed to predict time in queue using these variables: demand volume, percentage of vehicles in closed lane, existing demand, existing demand plus queue arrivals, queue length, volume in closed lane, and volume in open lane. The models developed for each type of work zone TCP were compared by assessing the confidence intervals of the regression equation coefficients.

Results indicated that throughput volumes were not statistically different for the late merge signing and MUTCD TCPs. Models developed for time in queue were also not statistically different. The researchers also reported that when queue lengths are short, the MUTCD TCP had shorter travel times while, with longer queue lengths, the late merge signing TCP resulted in shorter travel times. The differences, however, were small.

The researchers also noted that drivers did not adopt turn-taking as had been hoped and that lane straddling was still present, particularly with larger trucks. Although the late merge signing did not appear to offer any benefits in this situation, the lack of impact may be due to the short time drivers had to acclimate to the strategy.

In a related study, Beacher et al. (2005) used simulation to assess the impact of the late merge traffic control strategy. The traffic microsimulation model, VisSim, was used to model a three-to-two, three-to-one, and two-to-one work zone configuration using a 6 mile link of roadway with no access points. A traditional MUTCD TCP and late merge signing TCP were developed for each strategy. Models were developed to vary volume, percentage of trucks, and desired free flow speeds. The models were calibrated using field data.

The researchers used a full factorial analysis to test for significance between individual factors and for interactions among factors to compare the late merge strategy with traditional MUTCD traffic control.

Comparison of strategies for the two-to-one lane configuration indicated no statistically significant difference between throughput for the late merge signing and MUTCD TCPs in most instances. When heavy truck percentages increased, small improvements in throughput were noted for the late merge signing TCP.

Results for the three-to-two lane configuration indicated that the MUTCD TCP produced higher throughputs for most scenarios as compared to the late merge signing TCP. When truck percentages increased more than 20 percent and the lane closure was over capacity, the late merge signing outperformed the traditional TCP.

The researchers found that the late merge resulted in a statistically significant increase in throughput volume for a three-to-one lane closure configuration given that available capacity appeared to be maximized while unused gaps were minimized.

A Nebraska Department of Roads (NDOR) study identified uses for early and late merge signing strategies. The early merge strategy encourages drivers to merge into the open lane sooner than the typical TCP used by NDOR, while the late merge signing strategy encourages drivers to remain in their lane until they reach the merge point at the lane closure taper. McCoy and Pesti (2001) assessed the advantages and disadvantages of each measure.

Early merges are indicated either by static or dynamic messages. Static signs are placed approximately at one-mile spacing for several miles in advance of the lane closure. They provide early messages to drivers to reduce the chance that they will encounter congestion before normal work zone signing has alerted them to potential problems. Drivers are then able to merge in advance of lane closures. Some states use devices such as lane drop arrows, rumble strips, and no passing zones one or more miles in advance of the lane closure to discourage drivers from passing in the closing lane.

Nemeth and Rouphail (1982) conducted simulation modeling and found that early merge TCPs significantly reduced the number of forced merges particularly at higher volumes. Mousa et al. (1990) also conducted simulations and found that travel times through the work zone were increased with the strategy because vehicles that follow slower vehicles are delayed for a greater distance than if they had waited to merge at a later point. The researchers suggested that this may increase the probability of queue jumping.

Dynamic messaging has also been used with the early merge strategy. A system used by the Indiana DOT (INDOT) created a dynamic no-passing zone to encourage drivers to merge early and stay in the open lane. The system uses detectors to determine when a queue is present in the early lane and Do Not Pass signs activate. The signs are placed adjacent to the closed lane at 0.25 and 0.5 mile intervals for 2.5 miles upstream of the lane closure (McCoy and Pesti 2001).

NDOR used field studies to compare their traditional TCP with the INDOT early merge TCP. They found that vehicles moved into the open lane sooner with the early merge and that the merging was more uniform over a longer distance. Merging with their traditional TCP occurred over about a 500 ft section around 1,200 ft upstream of the lane closure. NDOR found that only 0.44 forced merges per hour occurred with the early merge, while 20 or more per hour occurred with the traditional TCP under similar volume conditions (McCoy and Pesti 2001).

NDOR also compared the operation and safety of the PennDOT late merge configuration with their traditional TCP. They found that conflict rates were lower with the late merge and that under higher densities, about 75 percent fewer forced merges and 30 percent fewer instances of lane straddles were observed. They also report that work zone capacity was almost 20 percent higher with the late merge configuration. (McCoy and Pesti 2001).

However, McCoy and Pesti (2001) expressed concerns that during off-peak periods, when capacity is low and speeds are higher, drivers may have a more difficult time establishing who has the right of way, which creates a potential for collisions at the merge point. They suggested use of a dynamic late merge system may resolve the problem.

7.3 Measures to Reduce Speeds in Work Zones

Finally, the following measures have been used to manage speeds in work zones. This section summarizes recent literature on speed management techniques in work zones.

The research team also recently completed a project that summarized traffic-calming treatments in work zones, including static signing, dynamic signing, automated flaggers, public awareness, policy and enforcement, pavement marking treatments, and intelligent transportation system technologies. (The report is available at http://www.ctre.iastate.edu/research/detail.cfm?projectID=1199717207).

7.3.1 Automated Speed Enforcement

The Maryland State Highway Administration (SHA) tested automated speed enforcement (ASE) in work zones (Franz and Chang 2011). Two mobile ASE units were deployed in October 2009 at three sites in the Baltimore–Washington DC area. The trailers were first placed for 30 days where only warning tickets were issued. Warnings were issued for drivers traveling 12 or more mph over the work zone speed limit. Media campaigns were used at the same time. After the 30 day grace period, tickets were issued to the registered owners of speeding vehicles.

Data were collected before and after deployment of the ASE. Data were collected upstream, at, and downstream of the ASE unit. The study evaluated mean speed, 85th percentile speed, driver traveling 1 mph over the posted speed limit, driver traveling 1 to 10 mph over the posted speed limit, and drivers traveling 10 or more mph over the posted speed limit. Data were collected for one direction of travel at each of the three work zones. Due to problems with data collection, not all data collection locations were available at each site.

At one, the ASE for I-195 Express Toll Lane (ETL) mean speed was reduced from 58.6 to 55.2 mph (or 3.4 mph) with no change in 85th percentile speeds. The percentage of drivers traveling 1 to 10 mph over the posted speed limit decreased by 15.3 percent (from 60.0 to 44.7 percent) and the percentage traveling more than 10 mph over decreased by 7.7 percent (12.1 to 4.4 percent).

At the second site, I-195 at Intercounty Connector (ICC), mean speed decreased by 1.9 mph (63.2 to 61.3 mph) from before use of the ASE to after with no change in 85th percentile speeds. The percentage of vehicles traveling 1 to 10 mph over the posted speed limit decreased by 5.8 percent (from 34.9 to 29.1 percent), while the percentage traveling more than 10 mph over increased slightly (1.1 percent) from 3.0 to 4.1 percent.

Before data were not available at the third site.

ASE has also been used by DOTs in Arizona, Oregon, and Washington.

An ASE system was also evaluated in Illinois (Hajbabaie et al. 2011). Four enforcement/automated enforcement systems were tested:

- Speed feedback sign mounted on a trailer
- Stationary patrol car with emergency lights off
- Stationary patrol car with trailer mounted speed feedback sign
- Speed photo-radar enforcement (SPE) system mounted in a van alongside the roadway

The authors evaluated two Illinois work zones, one on I-64 and one on I-55, where bridge deck repair was underway. The posted speed limit was 55 mph for the work zone and both were about 7 miles long.

Data were collected using a video recorder with markers placed at measured distances apart in a straight section of the work zone. Data were collected with no treatments in place (control) and with each treatment in place during the same times and days of the week. The speed feed trailer recorded reductions from 1.8 to 2.0 mph for passenger vehicles with only marginal changes for large trucks. With the police car only, speed reductions were 6.8 to 7.8 mph for cars and 2.1 to 4.4 mph for trucks. Reductions for the treatment with both the police car and speed feedback sign were similar to just the police car, with decreases from 7.2 to 7.7 mph for passenger cars and 3.3 to 5.2 mph for trucks. Finally the SPE system had the greatest decrease with reductions of 7.8 mph for all periods for passenger cars and decreases from 3.9 to 5.8 mph for trucks.

7.3.2 Speed Enforcement

Wasson et al. (2011) used Bluetooth probe data acquisition stations in a work zone to select a random sample of vehicles to compare speeds for one day without enforcement to one day with heavy enforcement (12 enforcement vehicles in and adjacent to the work zone). Data were collected for about 11 percent of passing vehicles. While enforcement was in place, mean speeds were reduced by around 5 mph. However, even at the peak of enforcement, about 75 percent of vehicles were still exceeding the posted speed limit of 45 mph.

Finally, as noted in section 7.3.1, an evaluation of various enforcement and automated enforcement methods indicated that presence of a stationary patrol car with emergency lights off reduced speeds significantly (Hajbabaie et al. 2011).

8. RECOMMENDATIONS

The team met with the technical advisory committee (TAC) at the conclusion of the project and reviewed project findings. The team and members of the TAC developed recommendations for future actions that could be tried to address the operation and safety work zone challenges identified.

Use of late merge, described in Section 7.2, was indicated as one potential recommendation to address changing the behavior of drivers who try to queue jump or block other vehicles. It was indicated that the late merge had been used in Minnesota, as shown in Figure 8.1. Late merge encourages drivers to use both lanes until near the merge point and then to alternate merges. This encourages drivers who are likely to lane straddle to cooperate rather than engage in policing behavior. It is not likely to be effective under lower volume conditions.

Figure 8.1. Use of late merge in Minnesota (Images courtesy of Willy Sorenson, Iowa DOT)

One of the major behaviors leading to safety and operational problems that was identified was lane straddling by vehicles in an attempt to prevent other vehicles from merging. The team proposed use of longitudinal rumble strips down the lane line separating the closing and merging lanes as shown in Figure 8.2. This is similar to a centerline rumble strip and would discourage vehicles from repeatedly crossing the lane line. It may also discourage queue jumpers. Temporary rumble strips are available that can be placed for the duration of the work zone.

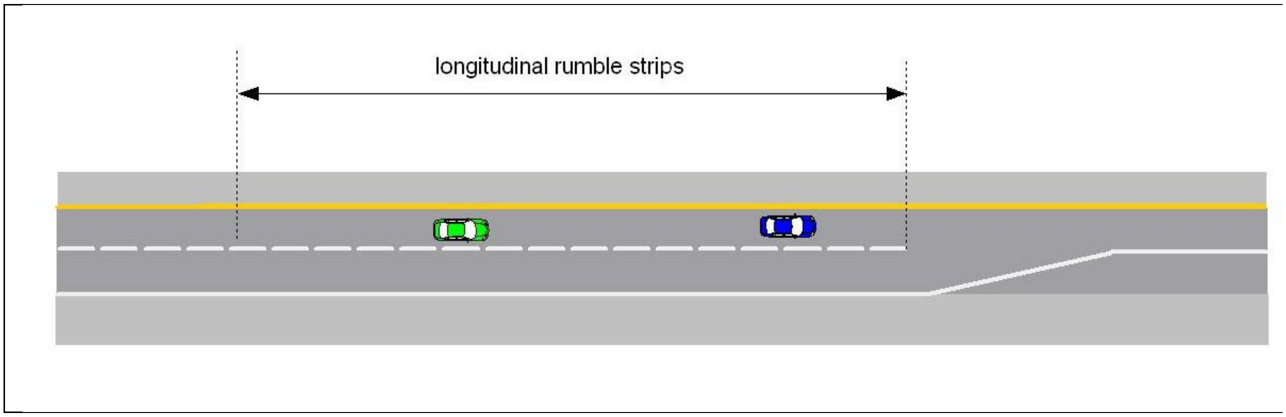


Figure 8.2. Use of longitudinal rumble strip

Use of transverse rumble strips in the closing lane as drivers approach a certain distance from the merge point was suggested as one method that may reduce the number of late merges as shown in Figure 8.3. Members of the TAC indicated that portable transverse rumble strips, which would be appropriate for freeway use, were available. Signing would be necessary to alert drivers they were approaching the rumble strips to encourage them to move over to avoid crossing the strips. Neither of the rumble strip options have been tried in a work zone as far as the team is aware.

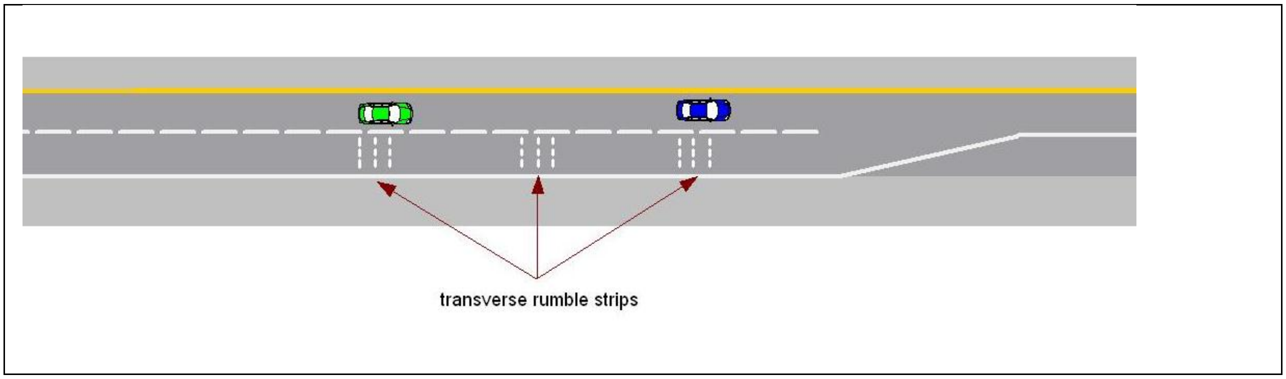


Figure 8.3. Use of transverse rumble strip

Finally, members of the TAC suggested use of a left lane merge followed by a lane switch, instead of a right lane merge. Because more traffic typically occupies the right lane, this would minimize the total number of merges and may help reduce late merges and aggressive behavior. The concept is depicted in Figure 8.4. TAC members believed this concept had been used in Iowa, but no specific examples of its use were documented.

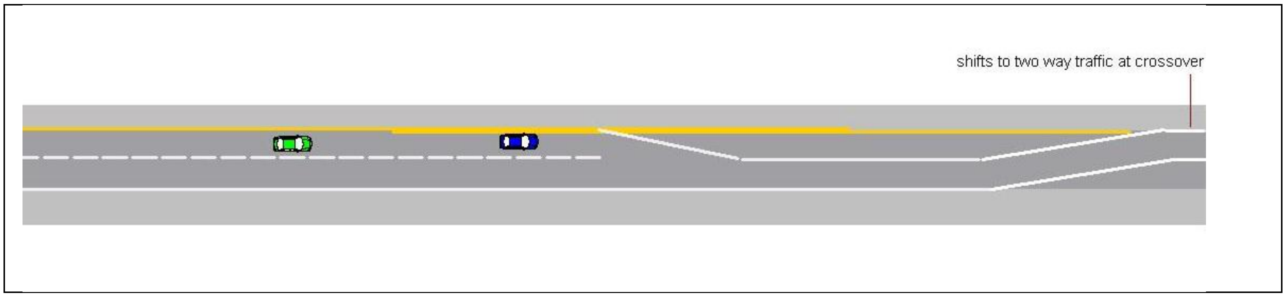


Figure 8.4. Left lane merge

As indicated, several solutions were proposed but their use has not been widely evaluated. Consequently, further research to document the effectiveness was proposed.

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