

Modeling Merging Behavior at Lane Drops

Final Report
February 2015

SWZDI 
Smart Work Zone Deployment Initiative



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Research and Education

IOWA STATE UNIVERSITY
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Iowa, Kansas, Missouri, and Nebraska created the Midwest States Smart Work Zone Deployment Initiative (SWZDI) 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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MODELING MERGING BEHAVIOR AT LANE DROPS

**Final Report
February 2015**

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- Iowa (lead state)
- Kansas
- Missouri
- Nebraska
- Wisconsin

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EXECUTIVE SUMMARY

Background

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

Problem Statement

In work-zone configurations where lane drops are present, merging of traffic at the taper presents an operational concern. In addition, as flow through the work zone is reduced, the relative traffic safety of the work zone is also reduced. Improving work-zone flow-through merge points depends on the behavior of individual drivers.

Goal and Objectives

The goal of this project was to improve work-zone driver-behavior models, particularly near the merge point. To accomplish this goal, the objectives of this effort were as follows:

- Identify work-zone merge countermeasures appropriate for the Midwest
- Develop and calibrate microsimulation models to better incorporate realistic and accurate driving behavior for merging
- Apply the model for different work-zone plans and countermeasures and determine their impact on driver behavior

Research Description/Methodology

A comprehensive literature review was conducted to summarize information about the effectiveness of work-zone strategies to address merging behavior leading to increased operations and improved safety. The team also conducted a survey of agencies in the Midwest to determine which countermeasures are regularly used as well as which innovative strategies have been considered.

One chapter of the report provides a review of the following strategies, which have been used to encourage desirable lane-merge behaviors to improve traffic flow and safety at work-zone merges:

- Variable speed limits
- Temporary rumble strips
- Static late merge
- Dynamic early-merge and late-merge systems

For each strategy, the information includes background, application (with a focus on information from the Midwest agency survey), effectiveness, advantages, and disadvantages.

Another chapter describes data collection and reduction as well as modeling development and calibration of an urban and an Interstate work-zone microsimulation model in VISSIM. The two Iowa work zones, one on Lincoln Way in Ames and the other on I-35 in Hamilton County, were modeled in VISSIM using real-world speeds, travel times, queue lengths, and merging behaviors.

These models were calibrated to reflect real-world queue lengths, speeds, travel times, and percentage of vehicles merging upstream and near the merge point. Once built and calibrated, strategies for the various countermeasures were modeled in the work zones. The models were then used to test and evaluate how the various merging strategies affect safety and operations at the merge areas in these work zones.

Key Findings

For the Interstate work zone, the early-merge scenario was found to make speeds more consistent and reduce both queue lengths and queue stops. It made merging smoother than the real-world scenario. It did, however, decrease speeds upstream more and pushed the queue farther away from the merge point. It was modeled based off a perfect scenario where all drivers would merge early, which in real life would most likely not be the case, so results in the real world would not be expected to be as great.

The late-merge scenario also improved operations for the Interstate work zone, by decreasing travel time, queue lengths, and queue stops. Speeds at the merge point were lower than with the real-world scenario, which is a potential safety benefit.

For the urban work zone, only the late-merge scenario was tested. It was found to decrease operations by slightly increasing travel time, and all queue lengths.

The real-world merging behavior for this work zone greatly resembled the early-merge strategy, which saw improved operations compared to the late-merge strategy for the Interstate scenario. This may help to explain the decrease in operations seen with the late-merge strategy at this work zone.

The early-merge strategy was not tested for the urban work zone as the majority of drivers already merged early with none merging within 200 feet of the merge point.

Conclusions

Overall, both the early-merge and late-merge strategies were found to improve operations and to smooth flow at the merge points in the work zone. Queue lengths, which pose safety concerns if

they extend too far upstream, because they can surprise drivers who are not expecting or aware of the work zone ahead, were decreased in both situations.

The early merge was found to be a good option when there was moderate congestion as it smoothed speeds and had shorter queues and travel times than the late-merge or real-world options. If vehicles increased, however, this option could extend queues farther upstream, which could result in longer queues.

The late-merge option did improve operations over the real-world scenario and may have been a better option if more vehicles were present.

Implementation Benefits and Readiness

Traffic control plans, work-zone policies, and countermeasures can be better targeted to reinforce desirable lane-closure merging behavior, leading to both improved safety and work-zone capacity, by better understanding driver behavior. A better understanding of the merging behavior of drivers will lead to the development of better lane-drop traffic-control plans and strategies, which will provide better guidance to drivers for safer merging.

Results of this research may be useful to the Smart Work Zone Deployment Initiative (SWZDI) departments of transportation (DOTs)—Iowa, Kansas, Missouri, Nebraska, and Wisconsin—as well as counties and cities. Some avenues to pursue in sharing the project results are to work further with the Iowa Local Technical Assistance Program (LTAP), the SWZDI panel, the Federal Highway Administration (FHWA), particularly given SWZDI is an FHWA Pooled Fund Study, and others to conduct further technology transfer of the results.

Selection and appropriate application of strategies will result in better output from work-zone traffic analysis tools. In turn, better output will lead to more-robust estimations of the impacts of a particular work-zone configuration. This will allow more effective and efficient traffic control plans to manage traffic around work zones and adjacent routes.

Improved evaluation of alternatives will ultimately lead to decreased congestion and improved travel time and mobility through work zones, benefiting agencies, workers, and the traveling public.

1. BACKGROUND

1.1 Introduction and Objectives

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

In work-zone configurations where lane drops are present, merging of traffic at the taper presents an operational concern. In addition, as flow through the work zone is reduced, the relative traffic safety of the work zone is also reduced. Improving work-zone flow-through merge points depends on the behavior of individual drivers. By better understanding driver behavior, traffic control plans, work-zone policies, and countermeasures can be better targeted to reinforce lane-closure merging behavior, leading to both improved safety and work-zone capacity.

The goal of this project was to improve work-zone driver-behavior models, particularly near the merge point. A better understanding of the merging behavior of drivers will lead to the development of better lane-drop traffic-control plans and strategies, which will provide better guidance to drivers for safer merging.

To accomplish this goal, the objectives of this effort were as follows:

- Identify work-zone merge countermeasures appropriate for the Midwest
- Develop and calibrate microsimulation models to better incorporate realistic and accurate driving behavior for merging
- Apply the model for different work-zone plans and countermeasures and determine their impact on driver behavior

1.2 Disruptive Driver Behaviors

A previous study by Hallmark et al. (2011) evaluated which driver behaviors result in the greatest reduction of capacity with work-zone lane closures. Data were collected at work zones for six days to identify behaviors that affected work-zone safety and operations, including 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, drivers 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 documented, 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.

1.3 Summary

A comprehensive literature review was conducted to summarize information about the effectiveness of work-zone strategies to address merging behavior leading to increased operations and improved safety.

The team also conducted a survey of agencies (Iowa, Kansas, Missouri, Nebraska, and Wisconsin) in the Midwest that are part of the Smart Work Zone Deployment Initiative (SWZDI), which is a Federal Highway Administration (FHWA) pooled fund study, to determine which countermeasures are regularly used, as well as which innovative strategies have been considered.

Chapter 2 summarizes strategies that have been used to improve traffic flow and safety at work-zone merges and the application of these strategies by the SWZDI participants, in particular.

Chapter 3 describes the development and calibration of an urban arterial and an Interstate work-zone microsimulation model in VISSIM. Data collection and reduction as well as modeling development and calibration are discussed. Strategies discussed in Chapter 2 are modeled in these work zones and evaluated to see how they affect safety and operations at the merge areas.

2. SUMMARY OF COUNTERMEASURES USED TO IMPROVE WORK-ZONE MERGING

This chapter provides a review of various strategies that have been used to encourage desirable lane-merge behaviors. Information from the literature review and from the survey of agencies in the Midwest that are part of the Smart Work Zone Deployment Initiative (SWZDI) Federal Highway Administration (FHWA) pooled fund study (Iowa, Kansas, Missouri, Nebraska, and Wisconsin) is summarized for the following countermeasures:

- Variable speed limits
- Temporary rumble strips
- Static late merge
- Dynamic merge system (early-merge and late-merge systems)

Each section includes the following information:

- Background
- Application (with a focus on information from the Midwest agency survey)
- Effectiveness
- Advantages
- Disadvantages

2.1 Variable Speed Limits

Background

Although not specifically a work-zone merge countermeasure, variable speed limit (VSL) systems have been used to improve flow and safety in work zones and other areas. VSL systems use detectors to assess traffic and other conditions and then dynamically display speed limits appropriate to the conditions. Appropriate speeds are typically based on traffic conditions but can be based on weather and road surface conditions as well. Automated algorithms are used to determine whether a change in speed limit is likely to improve traffic conditions (Fudala and Fontaine 2010). The objective of VSL systems is to reduce speed variance and improve speed compliance.

Application

Iowa, Kansas, Nebraska, and Wisconsin reported no experience with VSL systems as a work-zone merge countermeasure. Current laws do not allow use of VSLs in Nebraska and Wisconsin. Edara et al. (2013) conducted a survey of state departments of transportation (DOTs) and also reported that Indiana and Michigan have not used VSLs.

The University of Missouri conducted a study using a VSL system in Missouri, but Missouri has not used VSLs since. (Additional information about the study is included later in the section below.)

Effectiveness

Fudala and Fontaine (2010) conducted a calibrated simulation to assess the performance of a field application of a VSL at a high-volume, congested work zone along an urban Interstate in northern Virginia in 2008. The field system had a static 55 mph speed limit that was posted at the site prior to installation of the VSL. VSLs were only utilized when lanes were closed. At other times, the system displayed a static 55 mph. When operating, the system had a maximum allowable speed of 50 mph and a minimum of 35 mph. The work zone was separated into zones and speed limits within each zone were maintained at the same speed.

Speed, volume, and roadway characteristic data were obtained from the field including location of vehicle detectors and VSL sign locations. A network was developed in VISSIM and the system was calibrated using travel-time data collected during work-zone lane closures. Model and real-world travel times were compared and driving behaviors in VISSIM were modified until the two measures were within 10 percent, a commonly accepted calibration target. A vehicle-actuated programming interface in VISSIM was used to develop code that approximated driver behavior.

After calibration of the VISSIM model using field data, several different lane-closure configurations were evaluated. A base case with no VSL present and two different lane-closure

scenarios with different VSL control algorithms were configured. Each scenario was modeled under different input volumes and driver speed-limit compliance and time intervals (5, 10, and 20 minutes) between speed limit changes.

One scenario was a four-to-one lane closure and the other was a four-to-two lane closure. Each was modeled under different input volumes and driver speed-limit compliance and time intervals (5, 10, and 20 minutes) between speed limit changes. Two different types of VSL control were also evaluated against the calibrated base case.

Results for the four-to-one lane closures indicated that mean speeds for the base case and two different VSL control algorithms were similar, particularly during congestion. As a result, the researchers concluded that the VSL did not offer any operational advantages for this work-zone configuration. They found little variability in speed variance during congested conditions but found that the VSL could potentially reduce speed variability during free flow.

The VSL resulted in queue dissipations that were about 10 minutes earlier than for the base case. They also found that fewer lane changes were present with either VSL control strategy.

Results for the four-to-two lane closure found that in all case higher speeds were maintained with the VSL. The researchers also found that the standard deviation in speed was higher with the VSL but the authors felt that this may have been due to the low volumes present in the base case.

The average queue length was significantly lower for both VSL cases compared to the base strategy. The researchers found that the queue dissipated 1 hour earlier with the VSL and they found decreases in the number of lane changes.

The authors recommend that if VSLs are used in a work zone, they should be activated on a consistent basis to obtain maximum benefits. The real-world application that the authors evaluated was often not activated and they felt that drivers did perceive the VSL to be dynamic and that may have led to drivers disregarding it.

In St. Louis, Missouri, VSLs were used for congested and uncongested freeway work zones (Edara et al. 2013). The system averaged vehicle speeds every 30 seconds and displayed speeds at 1 and 2 miles upstream of the taper. The VSL was set based on average speed at the taper. One uncongested work zone and one control site were selected for evaluation.

Control sites were selected on a nearby freeway. Two detectors were placed upstream of the work-zone merge taper. The researchers found average speeds consistently lower at the VSL site than the control site. Speed drops were more predominant at the VSL site but speed deviation was higher at the VSL site. They found that speeds were 4 to 12 times higher with the VSL than without the VSL, average speeds were 2.2 mph lower with VSL than without, and standard deviation of speeds was 4.4 mph higher with VSL than without.

Several sections of the congested test and control site were also evaluated and speeds were measured at 2 points upstream and at the bottleneck. A ratio between the speed change at the two upstream locations and the upstream location and bottleneck was developed. A ratio greater than 1 indicated that higher vehicle speeds were present. The researchers found that speed reduction ratios were higher without VSL (0.7 to 1.32) than with VSL (0.14 to 0.57).

VSLs were also used along a freeway work zone in the Twin Cities, Minnesota (Kwon et al. 2007). Five radar sensors and three advisory speed limit signs with light-emitting diodes (LEDs) were used to vary the speed limit by 5 mph increments. The average speed difference between sensors was reduced from 13.0 to 8.4 mph after the VSL become operational for the 6 to 7 a.m. period and reduced by 18.4 to 14.1 mph from 7 to 8 a.m. In addition, average downstream throughput increased by 7.1 percent during the morning peak time.

Advantages

- Speed limit can be adjusted to reflect current traffic, weather, or work-zone conditions

Disadvantages

- Without enforcement, VSLs may not have much impact on driver behavior
- VSLs do not directly address negative driver work-zone merge behaviors

2.2 Temporary Rumble Strips

Background

Temporary rumble strips consist of a raised surface that is placed on or temporarily adhered to the pavement (ATTSA 2013). Several types of temporary rumble strips are typically used (see Figures 1 through 3).



Maxwell 2012

Figure 1. Two types of temporary rumble strips: adhesive (left) and portable (right)



Roads and Bridges n.d.

Figure 2. Portable rumble strips



Fontaine n.d.

Figure 3. Rumble strip tape

Preformed thermoplastic rumble strips are melted or fused to the pavement surface. Pavement marking tape is applied with adhesive and may be layered to the desired thickness. Manufactured rumble strips require an adhesive agent or screws and portable rumble strips have sufficient weight and are designed to stay in place after placed on the roadway surface.

Temporary rumble strips serve to draw driver attention to work zone warning signs prior to and within a work zone having lane restrictions, reductions, and/or sharp detour transitions (Harwood 1993). Rumble strips provide both a tactile and audible warning to reduce speed. Although rumble strips alert drivers, because they do not have a single standard use, they require additional traffic control to let drivers know what action they are supposed to take (Ray et al. 2008).

Rumble strips have been used at work-zone merges to alert drivers of ending lanes and to encourage them to move out of the closing lane. Temporary rumble strips have been used in cases where other countermeasures have not reduced late merges (Pigman and Agent 1998).

Application

Midwest Applications

Several Midwest states (Iowa, Kansas, Nebraska, and Wisconsin) have used temporary rumble strips in advance of flaggers or temporary signals, and Kansas is working on guidance for use of them in advance of flagger operations or temporary signals.

Missouri allows for temporary rumble strips on flagging operations, on lane closures on multi-lane roadways that merge, and on roadways with sight distance issues.

Kansas and Missouri have both used adhesive temporary rumble strips. But, Kansas does not recommend these for high speeds or high volumes. Kansas has also used three-piece and hinged rumble strips.

Kansas, Missouri, and Wisconsin have used RoadQuake-style rumble strips.

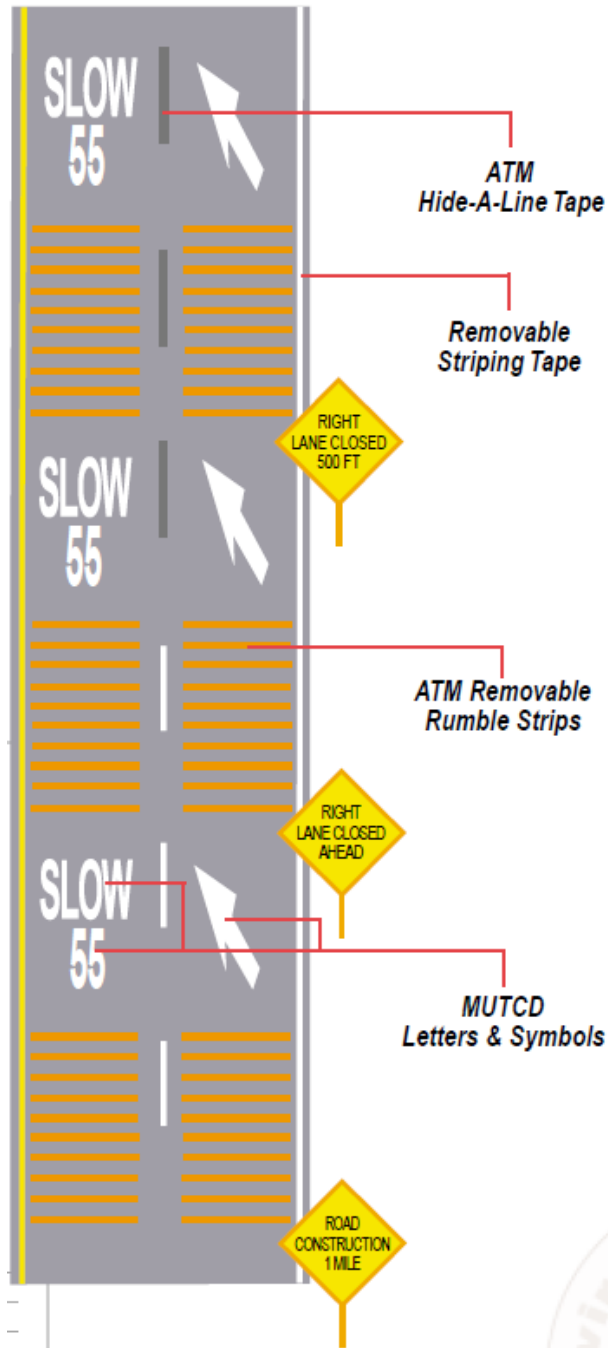
Other Guidance

The American Traffic Safety Services Association developed guidelines for use of temporary rumble strips in work zones (ATSSA 2013). The guidelines include information about the following:

- Selection of rumble strips (type, color)
- When temporary rumble strips should be used
- Location and configuration of rumble strips
- Placement of rumble strips (continuous versus wheel path only, pattern, spacing)
- Signing and messaging
- Maintenance

The ATSSA document is comprehensive and rather than summarize information here, please see ATSSA 2013 for additional information.

Most states have used rumble strips in advance of flaggers or temporary traffic signals. Rumble strips have been placed in the closing lane to encourage drivers to merge well in advance of the merge point. In particular, they discourage lane straddling, which can lead to forced and late merges. An example of a rumble strip configuration in advance of the merge point is shown in Figure 4.



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Figure 4. Removable rumble strip configuration for work-zone merge

Horowitz and Notbohm (2002) investigated the use of temporary rumble strips for reducing work-zone approach speeds prior to a temporary traffic signal at the intersection of a state and county highway in Wisconsin.

The Maryland DOT (MDOT) State Highway Administration (SHA) uses temporary transverse rumble strips to either alert drivers they are entering a work zone or to highlight other traffic control devices (MDSHA 2005). They provided the following guidance based on their experience and interpretation of the *Manual on Uniform Traffic Control Devices* (MUTCD):

- Temporary transverse rumble strips can be used in advance of detours, flaggers, lane splits, crossovers, lane transitions, exit-only lanes, lane closures, temporary traffic signals, and locations with major reductions in speed limit
- Temporary rumble strips are supplementary; they should be used in conjunction with other traffic control devices or visual cues which suggest the appropriate action
- RUMBLE STRIPS AHEAD signing should be placed in advance
- The strips should extend onto the shoulder to prevent drivers from going around them
- The closest set of strips should be placed 300 to 500 feet in advance of the work zone
- Caution should be exercised in areas with high motorcycle or bicyclist traffic
- They should generally not be used in short-term maintenance work zones
- After use, the strips should be removed and the pavement restored to normal condition

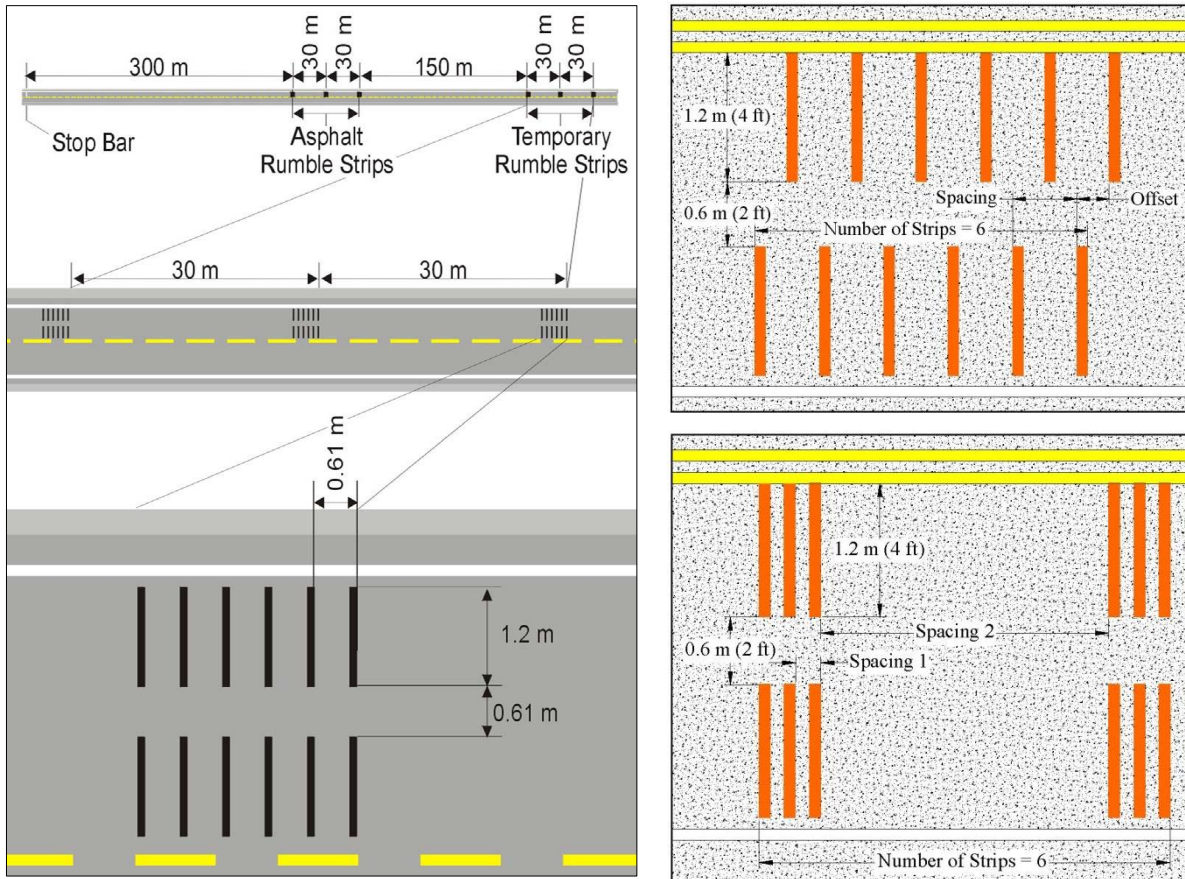
Effectiveness

Temporary rumble strips have been used in work zones in a variety of studies. Many, however, used rumble strips to alert drivers of upcoming stops (i.e., flaggers or traffic signal). As a result, the studies summarized below are not specifically for use of temporary rumble strips for work-zone merges.

Meyer (2006) investigated the noise level, speed reduction, vehicle vibration, and durability of two types of temporary rumble strips, as compared to asphalt rumble strips. Two work-zone sites, located in Horton and Perry Lake, Kansas, were selected, and rumble strips were placed in two eastbound and two westbound lanes. Both sites consisted of a rural two-lane highway where one through-travel lane was open and opposing-direction vehicles were required to stop.

The research team used a sound/vibration analyzer, accelerometer, microphone, and pneumatic road tubes to test the sites. The road tubes were deployed at the work-zone approaches before the stop point (no data were collected downstream of the rumble strips) for an average of 19 days, and the effects of vehicles platooned were removed.

Meyer found that all three treatment configurations (see Figure 5) showed a decrease in speed while the temporary rumble strips that were painted orange had the greatest effectiveness.



Meyer 2006

Figure 5. Temporary rumble strip configurations

Horowitz and Notbohm (2002) investigated the use of temporary rumble strips for reducing work-zone approach speeds prior to a temporary traffic signal at the intersection of a state and county highway in Wisconsin. The 12-set rumble strip was placed 1,106 feet away from the temporary stop bar in an area free of road cracks. Each rubber strip measured 4-foot wide by 0.25-inch high (see Figure 6).



Horowitz and Notbohm 2002

Figure 6. Temporary rumble strips

Three separate sets of data were collected, including vehicular speed, interior noise levels, and vibrations. Using a laser gun, speed data were collected prior to the intersection before and after installation for one day in three locations. The three checkpoints used were 554, 881, and 1,215 feet from the intersection. At 554 feet, average speeds were reduced from 42.9 to 41.8 mph (a 1.1 mph change statistically significant at 95 percent confidence level); at 881 feet, the average speed was reduced from 47.8 to 46.5 mph (a 1.3 mph change statistically significant at the 95 percent confidence level); and at 1,215 feet, the average speed was reduced from 49.9 to 48.6 mph (a 1.1 mph change not statistically significant at the 95 percent confidence level). The researchers concluded that the temporary rumble strips did not contribute to a substantial change in speed.

Similar conclusions were made by Richards et al. (1985) using temporary one-half-inch high polycarbonate rumble strips to reduce approaching work zone vehicle speeds on a rural two-lane, two-way highway in Texas. The investigators planned to install the rumble strips at two sites, but due to their inability to adhere to the pavement, only one site could be studied. The study evaluated the rumble strips in three different patterns. These included clusters of eight rumble strips with equal spacing, clusters of eight rumble strips with logarithmic spacing, and individual rumble strips spaced 52 to 66 feet at both sites, as described in a Federal Highway Administration (FHWA) report by Noel et al. (1989).

Speeds were collected at three locations for 125 vehicles (prior to, at, and in the work zone) using a digital stopwatch and 200 feet of observed roadway. Richards et al. (1985) reported that

the mean speed decreased by only 2 mph, indicating that the rumble strips were not an effective device.

In 2004, temporary transverse rumble strips were studied on a Maryland highway to alert drivers of unusual or unexpected road conditions. Research found that while driver awareness increased, the reduction in average speed was minor, and workers believed drivers were more aware of the activity in the work zone (Lessner 2005).

Wang et al. (2011) conducted a field evaluation of portable plastic rumble strips at three short-term maintenance work zones in Kansas. All were short-term work zones on two-lane highways. The researchers utilized three sets of four strips spaced at 36 inches. They found that the rumble strips reduced passenger vehicle speeds by 4.6 to 11.4 mph and mean truck speeds by 5.0 to 11.7 mph. They also found that about 5 percent of drivers swerved around the rumble strips.

Advantages

- Encourages drivers to merge in advance of the merge point
- Directly impact negative merge behaviors such as lane straddling or queue jumping
- Low cost

Disadvantages

- Noise
- Uneven surface for motorcyclists and bicyclists
- Potential for erratic movements by drivers attempting to avoid rumble strips or by drivers surprised by the rumble strips
- Potential movement of rumble strips when not properly applied (ATSSA 2013)
- Drivers may go around rumble strips

2.3 Static Late Merge

Background

Use of late merge has been used to increase capacity and reduce aggressive driver behaviors. Signing instructs drivers to continue using all available traffic lanes until they reach the work-zone taper. Static traffic-control signs also instruct drivers to take turns merging just before they reach the taper (see Figure 7).



Willy Sorenson, Iowa DOT

Figure 7. Use of late merge in Minnesota

The concept is that capacity increases by using all of the roadway space up to the work-zone taper (Beacher et al. 2004). The strategy was developed by the Pennsylvania DOT (PennDOT) in an attempt to reduce aggressive driving at merge points. The strategy 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.

McCoy and Pesti (n.d.) suggested that both late- and early-merge strategies provide lower conflicts than a traditional merge. However, they suggested there may be some confusion to drivers and the late merge may be problematic for high-speed and low-volume situations.

Application

Iowa, Nebraska and Wisconsin have not utilized the static late merge. The Missouri DOT (MoDOT) has not studied or used the static late merge. Based on studies from other states, MoDOT would allow this system as an option for projects if deemed appropriate by their districts.. Minnesota has used late merge in limited applications.

Effectiveness

Late merges are most effective when congestion is likely to be present. Under low volumes, late merges may increase conflicts at the merge point and increase travel time.

The strategy was evaluated in several different studies. McCoy et al. (1999) conducted a study in Pennsylvania at a two-to-one-lane-reduction scenario. Data were collected using video cameras and speed guns over four days. The authors 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 expectations. 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 (Walters and Cooner 2001). The researchers 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 feet 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.

Beacher et al. (2004) 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 to their suitability for project objectives. The site was a two-to-one-lane closure 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 feet before the arrow board. Speeds were further reduced to 25 mph about 1,000 feet past the taper.

The researchers collected volume data using traffic counters and temporary loop detectors, which were placed about 5,500 feet from the start of the taper (begin taper), 2,000 feet 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 the arrow board.

Both a standard 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 conventional merges. Models developed for time-in-queue were also not statistically different. The researchers also reported that when queue lengths are short, the conventional merge had shorter travel times, while, with longer queue lengths, the late-merge signing 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 (also in Beacher et al. 2004), the researchers 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. Conventional and late-merge signing 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 conventional 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 conventional signing in most instances. When heavy-truck percentages increased, small improvements in throughput were noted for the late-merge signing.

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

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.

Nemeth and Roupail (1982) conducted simulation modeling and found that early-merge strategies 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.

Advantages

- Increased work-zone throughput
- Increased capacity
- Directly addresses late and forced merges
- Reduced congestion

Disadvantages

- Drivers may have a more difficult time establishing who has the right of way creating a potential for collisions at the merge point
- Merge may be problematic for high-speed and low-volume situations
- May be difficult to get drivers to adopt turn-taking

2.4 Dynamic Merge System

Background

Dynamic messaging has also been used with the merge strategies. These systems use electronics and communications equipment to monitor traffic flow (speed, volume, occupancy) and, when queuing increases, the system regulates the merge by requiring either an early merge or a late merge (FHWA 2007).

A dynamic early-merge system creates a dynamic no-passing zone to encourage drivers to merge early and stay in the open lane. This helps reduce flow disruptions at the taper. Signs indicating that no passing is allowed in the closing lane are activated and may include flashing lights, changeable message signs, etc. If the traffic-monitoring device detects congestion, a signal is sent to the next sign upstream, which activates then forcing drivers to merge prior to the congestion.

A system used by the Indiana DOT (INDOT) uses detectors to determine when a queue is present in the open lane and activate Do Not Pass signs. The signs are placed adjacent to the closed lane at quarter- and half-mile intervals for 2.5 miles upstream of the lane closure (McCoy and Pesti 2013). This encourages drivers to merge into the open lane before reaching the end of queue and prohibits them from using the closing lane to pass vehicles queued in the open lane (Pesti et al. 2008). Some of the equipment for an early-merge system is shown in Figure 8.



Bushman and Klashinsky 2004

Figure 8. Typical dynamic lane merge equipment

A dynamic late-merge system, on the other hand, does the opposite of the early-merge system. Given that some concerns have been noted for static late-merge systems during off-peak times, a dynamic late-merge system only operates upon under-congested conditions.

The dynamic late-merge system consists of a series of advance signs which activate at set threshold conditions and advise drivers to remain in the lane until the merge point and then to alternate (Pesti et al. 2008). During off-peak times, the late-merge signing changes to regular work-zone advisory signing.

Application

Minnesota has conducted test deployments with dynamic late merge systems (MnDOT 2004). Iowa has experimented with dynamic late merge systems, but did not find it to be successful given prevailing volumes in Iowa. Iowa has not utilized the dynamic early-merge system however. Missouri has not used either system but would allow them as an option for projects if deemed appropriate by their districts, based on studies from other states.

Nebraska and Wisconsin have experimented with the dynamic late-merge system. Neither has tried the dynamic early-merge system. Kansas has considered it, but notes that Do Not Pass signs cause confusion so they are no longer using those with lane-drop signing in order for the dynamic merge signing to be consistent with the standard sign layout.

Effectiveness

Dynamic Early Merge

McCoy and Pesti (2013) evaluated dynamic early-merge systems. The system created dynamic No Passing, which used detectors to determine queues. Once a queue was detected the system encouraged drivers to merge into the open lane before reaching the end of the queue. 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 than for conventional merges. They also found that only 0.44 forced merges per hour occurred with the early merge, while 20 or more per hour occurred with a conventional merge under similar volume conditions.

The Michigan Department of Transportation (MDOT) utilized a dynamic early merge system during reconstruction of a large section of I-94 (FHWA 2004). The system monitored traffic flow and required early merging as queuing increased at merge points. The system consisted of five trailers, spaced at 1,500 feet) with sensors which detected traffic volume, speed, and detector occupancy. An index of activity (a function of volume, speed, and occupancy) was calculated and when current conditions exceeded a set threshold, the system activated Do Not Pass signs. Thresholds for each trailer were set based on their proximity to the merge point with lower thresholds for subsequently closer trailers. The trailer nearest the work zone continuously displayed Do Not Pass. The system was only utilized in the west bound direction since traffic

conditions in the eastbound direction would have resulted in continuous activation and MDOT felt this would lessen the systems effectiveness.

MDOT assessed performance of the system and recommended that the system was most effective for peak hour volume ranges from 3,000 to 3,500 vehicles per hour for a three-to-two lane merge. Results of probe vehicle runs indicated following:

- average number of stops decreased from 1.75 to 0.96 during the morning peak period with no change for the afternoon peak;
- no change in stopped time delay was noted for either the morning or afternoon peak periods;
- average morning peak period travel decreased from 95 to 69 seconds per vehicle for each 10,000 feet of travel;
- average number of aggressive driver maneuvers decreased from 2.88 per run to 0.55 for the afternoon peak period with no change during the morning peak period,
- average travel speed increased from 40 to 46 mph during the morning with no change for the afternoon peak period

Dynamic Late Merge

McCoy and Pesti (2013) also compared the operation and safety of the PennDOT late merge configuration with a conventional merge. 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.

Minnesota has conducted several test deployments with dynamic late merge systems. Three were deployed around the Minneapolis/St. Paul metropolitan area and one was deployed near Anoka, Minnesota (MnDOT 2004). Lane use instructions were dynamically changed based on current traffic demands. The system consisted of loop detectors and CMS signs which when activated displayed the following in order from the perspective of the driver: STOPPED TRAFFIC AHEAD — USE BOTH LANES, USE BOTH LANES — MERGE AHEAD, and MERGE HERE — TAKE TURNS.

The study reported that the percentage of drivers utilizing the discontinuous lanes increased dramatically when the system was activated. Increase of up to 60 percent were noted. However increases in volume throughput within the single lane construction closure were not noted. Additionally, they found lack of understanding with the system. In particular, large trucks were found to lane straddle in order to block vehicles from using the closing lane.

Advantages

The main advantage to dynamic merge systems is that the system can be tailored to address current traffic conditions.

Disadvantages

The main disadvantage to the dynamic merge systems is that drivers may be confused when the system is not activated. In addition, training drivers to early or late merge in some situations may cause them to behave the same in a conventional merge. For instance, use of a dynamic late-merge system in some areas of the state may cause drivers to treat conventional merge situations as a late merge, which could have safety and operational issues.

3. USE OF SIMULATION TO ASSESS WORK-ZONE STRATEGIES

Several work-zone merge strategies were identified and described in Chapter 2. Several field studies have been conducted for the various strategies, but the utility of the countermeasures under different geometric or operational characteristics is difficult to determine.

Microsimulation provides the ability to compare different scenarios at a much lower cost than conducting a field study. Within a microsimulation model, variables can be held constant except those which are being evaluated. This reduces variation in the analysis and allows us to test different lane configurations, different geometry (lane width, shoulder width), and different work-zone characteristics (distance to construction and ability to attribute the capacity impacts of individual variables). In addition, a range of values for a particular variable can be tested, which is not possible in the field.

As a result, one of the objectives of this study was to assess different strategies using microsimulation modeling. The merge countermeasures identified in Chapter 2 were assessed to determine which were viable for Midwest states and the most feasible for microsimulation modeling.

3.1 Simulation Studies for Work-Zone Merge Strategies

Several studies have used microsimulation to assess work-zone merge strategies:

- McCoy et al. (1999) used FRESSIM for the operational effects of the Indian Lane Merge (early merge) compared to no merge control strategy, as well as a constant half-mile no-passing zone in advance of the work zone.
- Beacher et al. (2004) used VISSIM to compare MUTCD treatments to the late-merge strategy using throughput volume as a measure of effectiveness.
- Zaidi et al. (2013) used VISSIM to evaluate dynamic merge systems. A two-to-one work-zone lane closure was modeled. Conventional work-zone planes were modeled along with dynamic early- and late-merging systems. Variable speed limits were also modeled.

3.2 Data Collection

Data were collected for two scenarios at work zones in Iowa. These two scenarios included lane drops at work zones on the Interstate and on an urban arterial roadway.

Interstate

The Interstate work zone was on a stretch of I-35 in Hamilton County, Iowa with annual average daily traffic (AADT) of 20,000. This site was chosen as it had a history of large queues occurring that sometimes were miles long on weekends.

The work zone involved the closure of the southbound lanes for approximately 6 miles. Due to the closure, southbound traffic crossed over to the northbound lanes and a head-to-head setup was utilized. A southbound lane drop of the right lane was in place upstream of the crossover to move all vehicles to the left lane.

Two cameras were used to collect data at this site. One camera was placed upstream of the lane drop approximately 0.85 miles while the other was placed near the end of the taper at the merge point. The approximate location of each camera, the beginning of the taper, and the crossover are shown in Figure 9.



Imagery: Landsat, Map data ©2012 Google Earth

Figure 9. Camera placement for I-35 work zone

The cameras were placed from September 12 to September 22, 2014 and collected continuous video during the time period. Due to the memory capabilities of the camera, only one weeks' worth of video data could be stored at one time. Therefore, even though the cameras were in place from September 12 to September 22, video data were only available for September 15 to September 22. Wavetronix units were placed on the camera polls and collected vehicle counts, speeds, and lengths in each lane.

Two hours' worth of data were extracted from the dataset. These included the hour where average speed was lowest, which was used to calibrate the work-zone model, along with another hour from a similar time frame, to use for validation purposes. These two hours were from 4:30 to 5:30 p.m. on Friday, September 18 for the calibration hour and from 5:30 to 6:30 p.m. on that same day for the validation hour.

While this merge point had a historical problem of queues forming on weekends, the one weekend we had camera data for, no queues occurred. The weekend we installed the cameras had queues according to the Wavetronix data, however we did not have the video data for this to determine the queue lengths or driver merging behavior. The Wavetronix data for the upstream location during this congested time period was also missing. Therefore, our peak period did not have any queues; however, it was congested with the average speed being 5.28 mph less than the posted speed limit just downstream from the merge point.

Urban Arterial

The urban arterial work zone was in Ames, Iowa on Lincoln Way, on the west side of town in a section of road with an AADT of 13,400 and four lanes with left turn lanes at intersections. The work zone was a little over one-quarter-mile long with shut downs of both eastbound and westbound directions at different stages during the project. With these closures, traffic was directed to the open direction in head-to-head traffic (see Figure 10).



Imagery: Landsat, Map data ©2012 Google Earth

Figure 10. Lincoln Way work-zone layout

A single camera was used to collect data for this work zone. The camera was used to capture westbound vehicles as they entered the taper. The camera was placed just past the taper as seen in Figure 10 and Figure 11.



Figure 11. Placement of the camera at the work zone

The urban arterial work-zone camera captured vehicles as they moved into the single lane in the left turn lane as seen in Figure 12.



Figure 12. Camera view of drivers merging in work zone

The taper began just west of Dotson Drive and was just upstream from the signalized intersection at Beedle Drive. This work zone was somewhat unique in that it had a signalized intersection approximately 400 feet upstream and then another signalized intersection just at the lane drop. The cameras were in place from Friday, August 1 to Monday, August 4.

One hour of data were extracted from the videos available on August 1 from noon until 1:00 p.m. This timeframe included heavy traffic and a queue that sometimes extended east of Dotson Drive.

3.3 Data Reduction

Interstate

Data were reduced for the hour by manually coding the videos at both the upstream and merge point. At the upstream location for the hour of interest, the number of heavy vehicles and all other vehicles in each lane (left and right) were counted. At the merge point, the number of heavy vehicles and all other vehicles were counted as well as the number of vehicles merging right before the start of the taper. Figure 13 demonstrates the views available from each camera.



Figure 13. Views from upstream (left) and merge (right) cameras on I-35

Wavetronic data were pulled for the two hours of interest. Average speeds for both cars and heavy vehicles were found as well as the combined average speed at the upstream and merge location. The data were also used to determine headways between vehicles and to develop speed distributions.

Urban Arterial

Data were reduced for the hour by manually coding the video. Traffic volumes were counted for all westbound vehicles as they passed the camera as well as eastbound traffic. The number of left-turning vehicles at Beedle Drive were estimated by looking at queue formations that occurred when traffic was freely moving westbound. The camera, unfortunately, was set just upstream of the intersection, so confirming these was difficult at times. Additional data were collected on the number of vehicles turning westbound onto Lincoln Way from Dotson Drive as well.

Queue lengths at the merge point were also determined and an average queue length was found. Capacity was determined by counting the number of vehicles that were serviced during two cycles where queues were continually present and not all vehicles in the queue were serviced during the cycle. Finally, free-flow travel times were also calculated using the video time stamps.

3.4 Model Development and Calibration

Interstate

The Interstate model was developed in VISSIM, a microsimulation software program that allows development of a model that can output data such as queue lengths and durations, travel times, delays, and so forth. Once the appropriate links and connectors were placed, the model was loaded with vehicles to make sure no errors in the coding were present.

Next, the driving behavior parameters were calibrated to make sure the capacity of the model was accurate. The definition of capacity in this study was taken from a study by Chatterjee et al (2009) and is the mean discharge flow rate sustained for the period of time for which the queue exists and is measured immediately downstream of the taper area. As data collected did not include the presence of queues, the Highway Capacity Manual (TRB 2000) was used to determine the capacity, which was approximately 1,550 vehicles per hour at the merge point. To calibrate the merge at the model, various driver behavior factors had to be changed, such as the headway reduction factor, turning on cooperative lane changing, and creating a merging behavior near the lane drop. This merging behavior was suggested by the PTV Group on their website (PTV Group n.d.) to create the merge in turn.

Once the model was calibrated for capacity, other areas were also calibrated. Speed was calibrated by developing desired speed distributions using real-world data. These desired speed distributions were developed by including the upper 95th percentile of speeds when the headway was greater than 4 seconds. Speeds were considered to be calibrated when the spot speeds were within 10 percent of the real-world data using the method described by the Oregon DOT (ODOT 2011). In addition, the area in which drivers merge was calibrated using the lane change distance and the vehicle routing choices.

Next, travel time was checked to make sure the model represented accurate times. While travel time data was not readily available from the field, it was estimated as close as possible using the timestamps on the videos. It was found that the average travel times fell within the 15 percent of the real world times as recommended by the FHWA Microsimulation Guidelines (Dowling et al. 2004).

Finally, the throughput, which was under 5 for all runs, was checked using the Geoffrey E. Havers (GEH) statistic, which is a formula used in traffic engineering, traffic forecasting, and traffic modeling to compare two sets of traffic volumes. Once the model was calibrated to satisfaction, the additional dataset from the hour immediately following was used to validate the model, again making sure that spot speeds, throughput, and travel time were within the acceptable targets.

Urban Arterial

The work zone was coded into VISSIM making sure to include the signals at Beedle Drive and at Dotson Drive. The signals were placed as fixed time as the actual signal timing plan was not available. This fixed timing plan was developed using standard times collected from the videos.

Once the network was appropriately coded, the model was run making sure there were no coding errors. Next, driving behaviors, speed, and acceleration distributions were calibrated to match capacity at the merge point. Speeds were also calibrated using travel time data collected from the video as speed data were not collected.

Once the capacity calibration was met, fine tuning calibration occurred to make sure the model accurately reflected queue lengths, both average and maximum, along with where drivers were merging into the open lane. Finally, throughput was again checked and was found to meet the GEH statistic requirements.

3.5 Evaluation

Interstate

Given that one of the objectives of this project was to assess the effectiveness of different work-zone configurations on capacity and safety, modeling times of heavy congestion will provide the best results. Given that no field data collected occurred during heavy congestion, the calibrated model's traffic volumes were inflated to produce the intended congestion. A traffic volume of 1,725 vehicles per hour was used to gather queue length, number of stops, travel times, and average speeds for the real-world scenario across 25 model runs. Additionally, the lane change data were collected and used to determine the number of forced merges. Forced merges were defined as those where there was 15 feet or less space between vehicles behind and in front of where the drivers wanted to merge. Once the data were collected, the model was changed to reflect two other work-zone strategies, the late-merge and the early-merge.

For the late-merge strategy, the model was manipulated to reflect 16 percent of vehicles merging from the right lane into the left open lane at or near the merge point. This 16 percent figure was chosen to reflect findings from McCoy et al. (1999) that showed approximately that percent of vehicles merged at the merge point in a late-merge strategy. It also reflects finding from Beacher et al. (2004), which saw 5.1 percent more vehicles in the closed lane at the merge when the late merge was present compared to the typical MUTCD merge. As the real-world condition saw approximately 11 percent merging near the lane drop, a 5.1 percent increase would be about 16 percent.

For the early-merge strategy the model was again manipulated so that no lane changes were allowed in the quarter mile upstream of the merge point. While this is not the exact way that dynamic early-merge systems work, when running the simulation, it was shown that the queue would never extend much beyond this length and definitely would not extend up to the half-mile

upstream location where the next sign would be placed. In addition, with the way the early merge was modeled, it assumed that all vehicles would be compliant, which might not be the case in the real world.

The same data as with the real-world model were collected for these two additional scenarios. The results of the three models are shown in Table 1.

Table 1. Results from merge strategies on I-35

Measure		Real-Life Conditions	Late Merge	Early Merge
Average speed ~0.8 miles upstream (mph)	Cars	56.48	56.5	44.18
	Heavy Vehicles	54.73	54.79	42.74
Average speed just downstream of merge point (mph)	Cars	39.37	35.66	48.48
	Heavy Vehicles	36.92	33.53	47.78
Average travel time (sec)	Cars	123.78	120.38	83.12
	Heavy Vehicles	124.98	121.14	84.8
Average queue length (ft)		860.11	622.01	110.66
Number of queue stops		1002	611	63
Forced merges per hour		35	28	2

As seen in Table 1, both the late merge and the early merge improved operations compared to the real-world conditions. The late-merge strategy saw speeds lowest near the merge point compared to the other two strategies, while the early-merge upstream speeds were much slower as vehicles are moving from the closed lane earlier. The early merge saw the smallest queues and the smallest change in speeds between the upstream location and the merge point. The average travel-time saving per vehicle for the late merge decreased by about 3 percent while the early merge decreased travel times by 30 percent. Forced merges also decreased in both the late-merge and early-merge cases with the early-merge only having approximately 2.

Urban Arterial

Unlike the Interstate scenario, the urban arterial scenario real-world data collection saw congestion and queues and therefore traffic volumes did not need to be increased beyond what was already present. Therefore, the final calibrated model was run for 25 runs of an hour each. During these runs, data were collected on average, maximum, and total queue lengths, travel times, and average speeds. The results of these runs are shown in Table 2.

Table 2. Results from merge strategies on Lincoln Way

Measure		Real-Life Conditions	Late Merge
Average speed 400 ft upstream (mph)	Cars	23.19	25.81
	Heavy Vehicles	21.05	23.44
Average speed at merge (mph)	Cars	22.62	21.60
	Heavy Vehicles	20.54	19.39
Average travel time from Dotson to Beedle (sec)	Cars	19.74	19.95
	Heavy Vehicles	17.96	20.99
Average queue length (ft)		73.85	77.28
Maximum queue length (ft)		177.68	180.28
Total queue length (ft)		443.11	463.66
Forced merges per hour		3	10

As with the Interstate model, the late-merge strategy was also tested at this work zone. Again, the real-world scenario was manipulated to allow for late merges. Unlike the late-merge Interstate scenario, this scenario allowed for all vehicles to merge from the late-closed to the open lane at the merge point. This was done as the previous research was for highway settings, so the results did not necessarily translate to an urban setting.

The rumble strip strategy was also considered as an alternative, but ultimately decided against being tested, as the operations at the merge point were greatly influenced by the capacity of the signalized intersections and decreasing speeds would not have improved operations.

The early-merge strategy was also considered but not implemented as drivers in the real-world scenario were almost all merging early. The same data were collected from the 25 simulation runs as in the real-world scenario. Again, results are summarized in Table 2.

The late merge slightly decreased operations at this urban arterial merge point. Average travel time increased by 1 percent for cars and 17 percent for heavy vehicles. Increases were seen in average queue length, maximum queue length, and total queue length by 5, 1.5, and 5 percent, respectively, with the late-merge configuration compared to the real-world merging.

As operations at this work zone are largely controlled by the two signals at the merge and just upstream, the late-merge strategy did not improve operations compared to the real-world data. The real-world merging behavior at this intersection also greatly resembled the early-merge

strategy, which saw improved operations compared to the late-merge strategy for the Interstate scenario. This may also help to explain the decrease in operations seen with the late-merge strategy at this work zone.

3.6 Modeling Driver Behavior Discussion

Modeling for driver behavior in a work zone begins by having good data on the behaviors of drivers in your area. Having information on speeds both upstream and near the merge point, a breakdown of vehicles and types per lane upstream and at the merge as well as the capacity of your work zone will result in better models. In addition, having advanced information such as queue lengths and acceleration values near the merge point can also improve your model.

Modeling a late merge can be accomplished by increasing the number of drivers who choose to merge late by changing the lane change distance, using a dummy connector and vehicle routing decision with a certain percentage of vehicles using that route or a combination of the two. It may be necessary to create a merging driver behavior near the merge point, which lets drivers be more aggressive in changing lanes as well. The PTV Group website lists a set of parameters that are recommended for late merges. If a dynamic late merge is to be tested, one needs to use a combination of partial routing decisions and vehicle actuated programming (VAP), which is described in Zaidi et al 2013.

Modeling an early merge can be done in a couple of ways. For instance, if you only want to model a static early merge, one can create a no lane-changing zone to allow for this. If this is done, the lane change distance should be increased as well as the emergency stop distance before the no lane-changing zone.

One can model a dynamic early merge using a similar approach to the dynamic late merge. This process is also described in Zaidi et al 2013.

4. CONCLUSIONS AND RECOMMENDATIONS

Two work zones, one located on I-35 in Hamilton County, Iowa and one located on Lincoln Way in Ames, were modeled and calibrated in VISSIM using real-world speeds, travel times, queue lengths, and merging behaviors (percentage of vehicles merging upstream and near the merge point). Once built and calibrated, these models were used to test and evaluate how merging strategies would improve safety and operations at these work zones.

For the Interstate work zone, the early-merge scenario was found to make speeds more consistent and reduce both queue lengths and queue stops. It made merging smoother than the real-world scenario. It did, however, decrease speeds upstream more and pushed the queue farther away from the merge point. It was modeled based off a perfect scenario where all drivers would merge early, which in real life would most likely not be the case, so results in the real world would not be expected to be as great.

The late merge also improved operations at the Interstate work zone, by decreasing travel time, queue lengths, and queue stops. Speeds at the merge point were lower than with the real-world scenario, which is a potential safety benefit.

For the urban arterial work zone, only the late-merge scenario was tested. It was found to decrease operations by increasing travel time, and all queue lengths. These increases were very small however. The decrease in operations may be due to the fact that the merge acted similar to an early-merge system in the real world, which saw better operations in the Interstate model compared to the late merge. The early-merge strategy was not tested for this scenario as the majority of drivers already merged early with none merging within 200 feet of the merge point.

Overall, both the early-merge and late-merge strategies were found to improve operations and to smooth flow at the merge points in the work zone. Queue lengths, which pose safety concerns if they extend too far upstream, because they can surprise drivers who are not expecting or aware of the work zone ahead, were decreased in both situations.

The early merge was found to be a good option when there was moderate congestion as it smoothed speeds and had shorter queues and travel times than the late-merge or real-world options. If vehicles increased, however, this option could extend queues farther upstream, which could result in longer queues.

The late-merge option did improve operations over the real-world scenario and may have been a better option if more vehicles were present. For the urban work zone, the late-merge strategy slightly decreased operations at the merge point.

REFERENCES

- ATSSA. 2013. *Guidance for the Use of Temporary Rumble Strips in Work Zones*. American Traffic Safety Services Association. Fredericksburg, VA. September 2013.
- Beacher, Andrew G., Michael D. Fontaine, and Nicholas J. Garber. 2004. *Evaluation of the Late Merge Work Zone Traffic Control*. Virginia Technical Research Council. Charlottesville, VA. August 2004.
- Bushman, R. and R. Klashinsky. 2004. *Deployment and Evaluation of ITS Technology in Work Zones*. Saskatoon, Saskatchewan, Canada.
www.workzonesafety.org/files/documents/database_documents/IRD.pdf
- Chatterjee, Indrajit, Praveen Edara, Sandeep Menneni, and Carlos Sun. 2009. Replication of Work Zone Capacity Values in a Simulation Model. *Transportation Research Record: Journal of the Transportation Research Board*. No. 2130. pp. 138–148.
- Dowling, Richard, Alexander Skabardonis, and Vassili Alexiadis. 2004. *Traffic Analysis Toolbox Volume III: Guidelines for Applying Traffic Microsimulation Software*. Federal Highway Administration. Washington, DC. June 2004.
- Edara, Praveen, Carlos Sun, and Yi Hou. 2013. *Evaluation of Variable Advisory Speed Limits in Work Zones*. Smart Work Zone Deployment Initiative. FHWA Pooled Fund Study. Washington, DC. August 2013.
- FHWA. 2004. *Intelligent Transportation Systems in Work Zones - A Case Study: Dynamic Lane Merge System Reducing Aggressive Driving and Optimizing Throughput at Work Zone Merges in Michigan*. Federal Highway Administration, Washington, DC. October 2004.
- FHWA. 2007. *Intelligent Transportation Systems for Work Zones: Deployment Benefits and Lessons Learned*. Federal Highway Administration. Washington, DC.
ntl.bts.gov/lib/jpodocs/brochure/14320.htm and
ntl.bts.gov/lib/jpodocs/brochure/14320_files/14320.pdf. Accessed January 2015.
- Fontaine, Michael D. n.d. *Innovative Traffic Control Devices for Improving Safety at Rural Short-Term Maintenance Work Zones*.
ops.fhwa.dot.gov/wz/workshops/accessible/fontaine.htm. Accessed January 2015.
- Fudala, Nicholas J. and Michael D. Fontaine. 2010. *Work Zone Variable Speed Limit Systems: Effectiveness and System Design Issues*. Virginia Transportation Research Council. Charlottesville, VA. March 2010.
- Harris, Lisa. 2014. *Temporary Rumble Strips Help Workers Feel Safer*. Kansas Local Technical Assistance Program (LTAP) at Kansas University Transportation Center. Lawrence, KS
- Hallmark, Shauna, Abhisek Mudgal, Tom Stout, and Bo Wang. 2011. *Behavior Study of Merge Practices for Drivers at Work Zone Closures*. Institute for Transportation, Iowa State University. Ames, IA. June 2011.
- Harwood, D. W. 1993. *NCHRP Synthesis of Highway Practice 191: Use of Rumble Strips to Enhance Safety*. Transportation Research Board, National Research Council. Washington DC.
- Horowitz, A. and T. Notbohm. 2002. *Evaluation of Rumbler, Preformed Rumble Strips*. Midwest Smart Work Zone Deployment Initiative. FHWA Pooled Fund Study. Washington, DC.
- Kwon, Eli, Daniel Brannan, Kahled Shouman, Cassandra Isackson, Bernie Arseneau. 2007. Field Evaluation of a Variable Advisory Speed Limit System for Reducing Traffic Conflicts in Work Zones. Proceedings of the 2007 Annual Meeting of the Transportation Research Board, Washington, DC.

- Lessner, A. 2005. Work Zone Innovations. Paper presented at the 2005 AASHTO Standing Committee on Quality Conference, Washington, DC.
- Maxwell, Stefanie D. 2012. *FDOT's Work Zone Fatality Reduction Strategies*. ops.fhwa.dot.gov/wz/workersafety/wzfrwebinar/fl/wzfr_fl.pdf. Accessed January 2015.
- McCoy, Patrick T., and Geza Pesti. n.d. *Dynamic Late Merge Control Concept for Work Zones on Rural Freeways*. ops.fhwa.dot.gov/wz/workshops/accessible/McCoy.htm. Accessed January 2015.
- McCoy, Patrick T., Geza Pesti, and Patrick S. Byrd. 1999. *Alternative Driver Information to Alleviate Work-Zone-Related Delays*. Nebraska Department of Roads. Lincoln, NE.
- MDSHA. 2005. *Use of Portable Changeable Message Signs with Speed Displays in Work Zones*. Maryland State Highway Administration. Hanover, MD.
- MDSHA. 2005. *Use of Temporary Transverse Rumble Strips in Work Zones*. Maryland State Highway Administration. Office of Traffic and Safety. Hanover, MD. August 2005.
- McCoy, Patrick T., Geza Pesti, and Patrick S. Bryd. *Alternative Driver Information to Alleviate Work-Zone-Related Delays*. 1999. Nebraska Department of Roads. Lincoln, NE.
- Meyer, Eric. 2004. *Construction Area Late Merge (CALM) System*. Midwest Smart Work Zone Deployment Initiative. FHWA Pooled Fund Study. Washington, DC.
- Meyer E. 2006. *Guidelines for the Application of Removable Rumble Strips*. Kansas Department of Transportation, Topeka, KS.
- MnDOT. *Evaluation of 2004 Dynamic Late Merge System*. Minnesota Department of Transportation. St. Paul, MN. December 2004.
- Mousa, R. M., N. M. Roupail, and F. Azadivar. 1990. Integrating Microscopic Simulation and Optimization: Application to Freeway Work Zone Traffic Control. *Transportation Research Record: Journal of the Transportation Research Board*. No. 1254.
- Nemeth, Z. A. and N. M. Roupahil. 1982. Lane Closures at Freeway Work Zones: Simulation Study. *Transportation Research Record: Journal of the Transportation Research Board*. No. 869. pp. 19-25.
- Noel, E. C., Z. A. Sabra, and C. L. Dudek. 1989. *Work Zone Traffic Management Synthesis: Use of Rumble Strips in Work Zones*. Federal Highway Administration. Washington, DC.
- Oregon DOT. *Protocol for Vissim Simulation*. Oregon Department of Transportation. June 2011
- Pesti, Geza, Poonam Wiles, Ruey Long (Kelvin) Cheu, Praprut Songchitruksa, Jeff Shelton, and Scott Cooner. 2008. *Traffic Control Strategies for Congested Freeways and Work Zones*. Texas Transportation Institute. College Station, Texas. October 2008.
- Pigman, J. G., K. R. Agent, J. A. Deacon, and R. J. Kryscio. 1989. Evaluation of Unmanned Radar Installations. *Transportation Research Record: Journal of the Transportation Research Board*. No. 1244. pp. 7-16.
- PTV Group. *PTV Vissim FAQs*. n.d. vision-traffic.ptvgroup.com/en-us/training-support/support/ptv-vissim/faqs/. Accessed February 2015.
- Ray, B., W. Kittelson, J. Knudsen, B. Nevers, P. Ryus, K. Sylvester, I. Potts, D. Harwood, D. Gilmore, D. Torbic, F. Hanscom, J. McGill, and D. Stewart. 2008. *Guidelines for Selection of Speed Reduction Treatments at High-Speed Intersections*. NCHRP Report 613. Transportation Research Board. Washington, DC.
- Richards, S. H., R. C. Wunderlich, and C. L. Dudek. 1985. Field Evaluation of Work Zone Speed Control Techniques. *Transportation Research Record: Journal of the Transportation Research Board*. No. 1035. pp. 66-78.

- Roads and Bridges. n.d. *Rumble Strips Survive Test of Cold*. www.roadsbridges.com/rumble-strips-survive-test-cold. Accessed January 2015.
- TRB. 2000. *Highway Capacity Manual*. Fifth Edition. Transportation Research Board of the National Academy of Sciences. Washington, DC.
- Walters, C. H., and S. A. Cooner. 2001. *Understanding Road Rage: Evaluation of Promising Mitigation Measures*. Texas Transportation Institute, College Station, Texas.
- Wang, C., K. K. Dixon, and D. Jared. 2003. Evaluating Speed-Reduction Strategies for Highway Work Zones. *Transportation Research Record: Journal of the Transportation Research Board*. No. 1824.
- Zaidi, Zaier, Essam Radwan, and Rami Harb. 2013. Safety Evaluation of Work Zone Including ITS Technologies Using Stochastic Micro-Simulation. 16th Road Safety on Four Continents. Beijing, China. May 2013.