USING SIMULATION TO EVALUATE THE PERFORMANCE OF SMART WORK ZONE TECHNOLOGIES AND OTHER STRATEGIES TO REDUCE CONGESTION

Alireza Kamyab, T.H. Maze, Mark Nelson, and Steven D. Schrock
Iowa State University
Center for Transportation Research and Education
2901 South Loop Drive, Suite 2100
Ames, IA 50010-8615
Phone: 515-294-8103
Fax: 515-294-0467
Email: markbne@iastate.edu

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ABSTRACT

This paper describes a microscopic traffic simulation model of an interstate work zone. This is a typical rural interstate highway work zone where two lanes are reduced to one lane in the work zone. This type of lane closure is common and, as traffic volumes build, a lane reduction creates congestion and results in vehicles queuing upstream from the lane merger.

The purpose of the simulation model is to assist in the evaluation of capacity enhancement and traffic management strategies to mitigate congestion caused by work zones lane reductions. The paper provides an example of the evaluation of a new traffic management technology, the Indiana Lane Merge System (ILMS), and discusses how the model could be utilized to evaluate other traffic management and capacity enhancement strategies.

INTRODUCTION

This paper describes a project we conducted to better understand driver behavior and traffic capacity of rural interstate work zone lane closures (from two to one lanes). The purpose of this research was to begin to develop tools to allow the Iowa Department of Transportation (Iowa DOT) to better plan and manage traffic when a freeway lane is closed for maintenance or construction activities. The intent of the Iowa DOT is to avoid, manage, and/or mitigate congestion resulting from lane closures in rural areas and, thus, to minimize the safety hazard caused by queuing vehicles on rural interstate highways. During the summers of 1996 and 1997, lane closures at rural work zones caused some of the worst congestion and delays experienced in Iowa. The congestion was probably also a contributing factor to several minor and severe crashes.

With better information on the capacity, delays, and merger behavior at lane closures, the Iowa DOT hopes to be able to better manage traffic. Ultimately, the organization would like to be able to manage traffic more proactively rather than waiting until congestion occurs to react with dynamic warning and advisory devices (e.g., changeable message signs warning motorists of stopped traffic). This is particularly important given the growth in traffic being experienced on Iowa’s rural interstate system. For example, traffic volumes on Interstate Highway 80 in rural eastern Iowa have increased by 44 percent from 1988 to 1997. This represents approximately a 4 percent increase per year. Daily bi-directional volumes have been recorded on rural sections of Interstate Highway 80 approaching 40,000 vehicles per day with trucks or other heavy vehicles accounting for as much as 35 percent of the traffic (1). Without new traffic management strategies, the increasing traffic volume will almost certainly result in even greater congestion and more hazardous conditions.

Traffic management practices at rural work zones vary little among states. The Iowa DOT sets up fixed warning signs as much as eight miles upstream of the merge point, use changeable message signs, and, in some cases, employs portable highway advisory radio to warn travelers of congestion. Without a better understanding of the behavior at work zones, transportation engineers and planners are unable to accurately understand the
dynamics of traffic at lane closures and it is, therefore, difficult for engineers and planners to justify more expensive countermeasures.

Strategies to mitigate lane closure induced congestion include both management strategies and physical capacity enhancements. A typical capacity enhancement is to provide additional capacity by adding lanes. Widening the roadway to allow more lanes through the work zone could require extensive preparatory work, such as widening and strengthening the shoulders to withstand heavy traffic levels and widening bridges. The decision to expend additional capital must be justified by the benefits that would be realized versus the cost. Another management strategy might be to encourage drivers, through the use of traveler information systems, to divert to alternative routes or travel at alternate times. Planning for the efficient use of diversion routes also requires accurate knowledge of the likely delay costs if traffic were not diverted versus the additional travel cost of the diversion route.

To develop an effective traffic management strategy, it is also necessary to understand driver behavior at the work zone, in other words, the impact of the vehicle merge discipline, or the lack of a discipline. Often, after a queue forms upstream from the merge point, aggressive drivers will travel in the closed lane to the head of the queue where they will wait for a gap or force their way into the through lane. This aggressive behavior causes a shock wave in the traffic in the through lane, reduces capacity, and increases the opportunity for crashes. The Indiana Department of Transportation has experimented with a dynamic system, which creates a no passing zone in the closed lane when a queue begins to build due to congestion. When the dynamic no passing zone is enforced, it eliminates late merging drivers, removes the shock waves caused by late merging vehicles, and therefore, increases the capacity of the work zone. The Iowa DOT would like to evaluate this system for use in Iowa.

Another issue of interest is a common practice by truck operators. Because late merging vehicles are seen as cheaters by drivers who patiently wait through the queue, two truck operators will commonly block both lanes by collaboratively traveling side-by-side, one truck traveling in the closed lane and the other in the through lane. As they approach the merge point, the truck in the through lane will let the truck in the closed lane move ahead and merge into the through lane. During one data collection session, this errant behavior was observed 18 times in one hour. This practice creates large gaps in the traffic stream between the side-by-side trucks and the vehicles immediately in front of them. The gaps reduce the overall traffic carrying capacity of the Interstate.

To evaluate the merge discipline described above and to provide a medium to test the delay cost savings of various management strategies, the Center for Transportation Research and Education (CTRE) at Iowa State University was asked to build and validate a microscopic simulation model. The model is a high fidelity computer simulation with an animation interface. It simulates traffic operation at a work zone merge area. This model enables traffic engineers to assess the delay resulting from shock waves introduced into the traffic stream, as well as, test the delay implication of various management strategies. The model also has the ability to vary many of traffic stream characteristics.
such as the percentage of trucks, the percentage of late merging vehicles, the traffic volume, and the percentage of passive drivers (drivers leaving large gaps between themselves and vehicles ahead of them).

**SIMULATING A RURAL WORK ZONE LANE CLOSURE**

Because no existing models would allow us to perform the experiments necessary for our evaluation, the decision was reached to develop and validate our own work zone traffic simulation model. The Texas Transportation Institute developed a computer program, Queue and User Cost Evaluation of Work Zones (QUEWZ) for the Texas Department of Transportation in 1985 and released an improved version in the early 1990s (2, 3). The primary output of this model is the estimate of delay due to lane closures. QUEWZ is widely used by many state highway agencies and is based on methods documented in the Highway Capacity Manual. QUEWZ is a macroscopic model, which uses a deterministic queuing model to estimate delays and queue lengths. A deterministic queuing model simply assumes that when the flow rate into the system is greater than capacity the difference is simply stored in the queue. The model treats vehicles stored in the queue like they are stacked immediately upstream of the merge point. As the rate of vehicles entering the system become less than the capacity of the work zone, the stack is dissipated. Although this is a widely used program and it is a valuable tool for estimating delays due to work zone lane closures, it does not model the dynamic behavior of vehicles, an essential component of our study.

Other microscopic traffic simulation models, such as CORSIM, can be used to model a work zone by treating the work zone lane closure as a roadway lane blocked by an incident. This, however, does not accurately represent the lane change activities on the approach to lane closure or the taper to the lane closure. Further, existing traffic simulation models do not allow for the incorporation of external logic, which would be necessary to simulate the impact of late mergers, slow moving vehicles and vehicle responses to traveler information.

With no existing model capable of effectively simulating driver behavior in the merge area, we decided to develop a microscopic model with a high fidelity graphical interface. The model design is based on the existing geometry of a rural work zone in which two lanes are reduced to one. The model also incorporates the traffic control devices and geometric standards used by the Iowa DOT for a work zone lane closure. Figure 1 shows the model’s layout of a workzone on Interstate 80 in Scott County, Iowa.
Data for the calibration of the work zone model were collected at a work zone on Interstate Highway 80 in eastern Iowa (on the outskirts of Davenport, Iowa) using two trailers equipped with boom-mounted video cameras. Once the video was collected, image-processing technology was used to reduce the images to data. A diagram of the data collection layout in the work zone and a picture of the data collection units are shown in Figures 2 and 3, respectively. All traffic data were collected during the summer of 1998.
Arena simulation software was selected for the development of the work zone lane closure (4). Arena is a powerful simulation modeling software with an advanced animation module. Arena is predominately used to simulate manufacturing processes. Because Arena is not designed specifically to simulate traffic, lane changing and car following algorithms had to be developed and incorporated into the model. The car-following logic depicts a driver’s behavior in responding to a lead vehicle in traffic flow. The lane-change algorithm is a more complex behavior as the decision to change lanes is dependent on a number of traffic stream conditions. Prior to changing lanes, a driver determines whether it is possible, necessary, or desirable to change lanes (5). In the model, as the vehicle approaches the workzone through the closed lane, it attempts to identify a sufficient gap in the through lane.

Within the model, each vehicle is generated according to an exponential distribution with an interarrival time of at least two seconds (i.e., two-second headway). Upon its arrival a number of attributes are assigned to the vehicle. These attributes include vehicle classification, speed, and lane assignment. The attributes are assigned following a discrete or continuous probability function. If, for example, it is assumed that trucks
make up ten percent of the traffic, the model randomly assigns truck characteristics to ten percent of the vehicles.

Vehicles enter the model several hundred feet upstream of the lane closure sign. It is, therefore, assumed that vehicles are well informed of the upcoming lane closure and the majority of the vehicles have merged into the through lane. There are, however, some drivers who will continue in the terminating lane and merge into the through lane when a gap is available near the head of the queue. A vehicle that is not able to merge before the lane is terminated must eventually stop at the beginning of the lane taper and wait for an acceptable gap. The waiting time for these vehicles is sometimes long because vehicles traveling in the through lane are not programmed to recognize the late merger and create a gap to allow the vehicle to merge. Drivers in the through lane do respond by adjusting their speed when a vehicle merges immediately in front of them. Merging into an insufficient gap creates a backwards moving shock wave in the traffic in the through lane.

**USE OF THE MODEL IN PLANNING TRAFFIC MANAGEMENT STRATEGIES**

The model will be used by the Iowa DOT to predict traffic conditions at future interstate work zone and to assist in the development of more proactive traffic management strategies. Since the model was calibrated using Iowa data, the model parameters are valid for estimating hours of delay for Iowa traffic. With the model and with information on historical traffic patterns, the Iowa DOT can begin to plan appropriate mitigation strategies.

Figure 4 shows a plot of traffic volumes taken from an automatic traffic recorder on Interstate 80 in eastern Iowa during the month of July, 1997, along with the capacity for single lane work zones in Iowa (1,216 vehicles per hour). At volumes well below 1,216 vehicles per hour, we expect free flow conditions. At volumes above 1,100 per hour but less than 1,200 vehicles per hour we would expect some congestion with short queues forming and dissipating. For flow rates above 1,200 vehicles per hour we expect sustained and lengthy queues to form.
Using the simulation model we can estimate the average and total vehicle delay in the queue. If the average delay is likely to only be a few minutes, the appropriate strategy may be to warn drivers of the need to stop and to provide traveler information stating that delays are likely to be less than 10 minutes (or some other appropriate time). However, if delays are likely to be long (e.g., longer than 25 minutes) it may be appropriate to warn drivers in advance so they can choose an alternative route or choose an alternative time to travel.

During the construction on Interstate 80 during the summer of 1996 and 1997 travelers experienced delays as long as two hours on rural highway segments. Traveler information may be delivered through highway advisory radio or other mechanisms to a broad enough geographical region so that travelers have ample distance and time to plan their trip and avoid the congested work zone.

As can be seen in Figure 4, the only time that diversion strategies or other traffic demand reduction strategies may be necessary would be on Friday and Sunday afternoons, when traffic flow entering the system significantly exceeds the capacity of the lane closure. The highway agency should then predict the total duration of significant congestion (e.g., the number days and hours per day for which significant delay can be expected.) and the level of delay motorist will incur. It would then be possible to compare the delay costs.
with the costs of diverting traffic and/or with the costs of alternative traffic management strategies (e.g., paving the shoulder to increase the useable width of the facility).

**EXPERIMENTS WITH THE MERGE DISCIPLINE**

Experiments were performed to better understand the impacts of the merge discipline behavior on delay. The two behaviors of interest are 1) using a variable no pass technique to require vehicles to merge upstream from the taper area and 2) measuring the impact of trucks traveling side-by-side, blocking late merging vehicles.

The Indiana Department of Transportation is experimenting with a variable no pass system, the Indiana Lane Merge System (ILMS). A drawing of the concept is shown in Figure 5 (6). The ILMS creates a variable no pass zone in the terminating lane. In other words, immediately upstream from the merge taper are static signs, which state “DO NOT PASS,” and one sign with flashing strobe lights (sign one in Figure 5) stating “WORKSITE DO NOT PASS WHEN FLASHING.” Thus, the first four signs create a static no pass zone. The signs upstream are dynamic in that strobe lights are activated when conditions warrant. A sensor is mounted on sign one to determine when the queue has reached it which trigger sign two. When the queue reaches sign two, sign three is activated and similarly the remaining signs are activated. This creates a dynamic no pass zone.

![Figure 5. Conceptual Drawing of Indiana Lane Merge System (6)](image-url)

To evaluate the dynamic no pass zone, we modified the simulation such that as soon as a queue begins to form in the through lane, the late mergers are no longer allowed to enter the terminating lane and must join the end of the queue. The simulation results indicate that by forcing the late mergers to join the end of the queue rather than allowing them to
force their way into the through lane at the head of the queue, the average speed is increased on the through lane.

For purposes of this simulation experiment, we consider only the 5,000 feet upstream of the merger taper as the approach corridor. The average speed and travel time in the approach corridor are measured before and after the dynamic no pass zone is implemented. The results of the simulation are shown in Figure 6. The results show a modest increase in average speed (about a five miles per hour increase in speed) and a reduction in the average travel times (a 12-second reduction in average travel time).

![Figure 6. Comparison of Dynamic No Pass Zone versus Base Case](image)

The variable no pass lane eliminates the backward moving shock waves created by late merging vehicles. Our experiments show that the ILMS has the potential to improve traffic flow at workzone, the improvement however would be modest. It should be pointed out that this system has only received limited field-testing. When field-tested, the evaluators found that because drivers were unfamiliar with the system, the confusion counteracted any benefits. Still, our experiments show that small system improvements are feasible.

Trucks traveling in both lanes side-by-side were modeled by modifying the simulation logic to capture this behavior. The base work zone model randomly generates slow moving vehicles in the through lane. These vehicles create large gaps between themselves and the vehicle immediately ahead of them. To model the impact of trucks traveling side-by-side in both lanes, when a slow moving truck was generated, a tandem vehicle is generated in the terminating lane. The two vehicles moved side-by-side to the head of the queue.

A comparison of the modified model to the base case did not produce a significant change in the traffic flow performance (average speed and average travel time) in the
approach corridor. This is partially due to the small number of late merging vehicles that this practice affects. This is also due to the fact that side-by-side trucks prevent late merging vehicles from forcing their way into the through lane. Therefore, any decline in performance due to trucks traveling side-by-side is offset by eliminating the shockwaves caused by the late merging vehicles.

**CONCLUSIONS**

A microscopic work zone simulation model was created and validated using traffic flow data collected in a rural interstate work zone. This model allows the user to evaluate devices and processes intended to improve the traffic flow through the work zone.

In addition to evaluating work zone technology, we see a significant benefit to being able to conduct planning in advance of congestion rather than simply reacting to congestion. As an example, the model can be used to predict the likely delay. The knowledge gained can be used by highway agencies in determining an appropriate level of response and in developing work zone specific traffic management plans.

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