# WORK ZONE SIMULATION MODEL

## Companion Report for
## "Traffic Management Strategies for Merge Areas in Rural Interstate Work Zones"
## CTRE Management Project 97-12

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CTRE
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Iowa Department
of Transportation

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# INTRODUCTION

To support the analysis of driver behavior at rural freeway work zone lane closure merge points, Center for Transportation Research and Education (CTRE) staff collected traffic data at merge areas using video image processing technology.  The collection of data and the calculation of the capacity of lane closures are reported in a companion report, "Traffic Management Strategies for Merge Areas in Rural Interstate Work Zones."  These data are used in the work reported in this document and are used to calibrate a microscopic simulation model of a typical, Iowa rural freeway lane closure.

The model developed is a high fidelity computer simulation with an animation interface.  It simulates traffic operations at a work zone lane closure.  This model enables traffic engineers to visually demonstrate the forecasted delay that is likely to result when freeway reconstruction makes it necessary to close freeway lanes.  Further, the model is also sensitive to variations in driver behavior and is used to test the impact of slow moving vehicles and other driver behaviors.

This report consists of two parts.  The first part describes the development of the work zone simulation model.  The simulation analysis is calibrated and verified through data collected at a work zone on Interstate Highway 80 in Scott County, Iowa.  The second part is a user's manual for the simulation model, which is provided to assist users with its set up and operation.  No prior computer programming skills are required to use the simulation model.

# PART I Work Zone Simulation Modeling Development

## INTRODUCTION

Simulation models are designed to duplicate the operation of an actual system. By simulating the functional characteristics of a system, these models are used to predict system performance for a variety of input scenarios. They make it possible to obtain information about the performance of a system through the running of simulated experiments. Performing similar experiments with actual systems may be cost prohibitive, disruptive, or impossible to complete.

Traffic operations are generally simulated through one of two categories of traffic simulations -- microscopic simulation and macroscopic simulation models. Macroscopic simulation regards traffic flow as a continuum or a stream of fluid. Microscopic simulation examines traffic flow by modeling the behavior of individual vehicles. Since microscopic simulation treats each vehicle as a unique entity, it provides a better medium for understanding the impact individual drivers have on the performance of the entire system. This provides a more effective tool for examining the impact driver behavior has on the throughput of work zones.

CORSIM and INTEGRATION are the two most widely used microscopic traffic simulation models (1,2). CORSIM was developed under Federal Highway Administration (FHWA) sponsorship. INTEGRATION was developed at Queens University in Ontario, Canada, as an integrated simulation and traffic assignment model. Both models can similarly predict the operational performance of an integrated traffic system consisting of local streets and freeway segments.

CORSIM and INTEGRATION can be adapted to simulate traffic operations around a work zone. This is done by assuming that a lane closure for a work zone results in the same type of impact on traffic carrying capacity as a lane blockage caused by an incident. Both programs are capable of simulating work zones through a prolonged incident blockage. This does not very accurately depict traffic behavior in the approach to a work zone. When modeling a lane blockage in CORSIM, the program assumes that drivers have no knowledge of the approaching blockage and there is no taper. INTEGRATION, on the other hand, does a better job of capturing an appropriate lane-changing behavior at work zones. It does not allow users to modify the location of advance warning signs.

These models do not allow the user to incorporate any external logic, which is necessary to simulate the impact of late merging and slow moving vehicles on the queue formation at work zones. These modeling limitations led to the decision to develop a work zone simulation model using Arena simulation software (3). Arena is a powerful simulation model with an advanced animation module and is typically used to simulate manufacturing processes.

## WORK ZONE SIMULATION MODEL

The work zone model design is based on the existing geometry of a typical interstate work zone with a lane closure, reducing two lanes to one. The model was based specifically on a work zone on Interstate Highway 80, located in Scott County, Iowa, during the summer of 1998. It is, however, flexible enough to accommodate the potential modifications of the work zone design and traffic characteristics. It also allows end-users to change parameters and conduct "what-if" analyses.

The work zone model is specifically designed to simulate traffic operations prior to and through a work zone. The two most important components of the model are the inclusion of car-following and lane-changing algorithms. The car-following logic models a driver's behavior in response to speed changes of the lead vehicle. The lane-changing algorithm is more complex because the decision to change lanes depends on a number of factors. Prior to changing lanes, a driver determines whether it is possible, necessary, or desirable to do so (4). It is necessary, for example, for a vehicle to change lanes when it approaches a lane closure. It is, however, desirable to change lanes when a vehicle is behind a slow-moving vehicle. The car-following and lane-changing algorithms will be discussed in the next two sections in more detail.

Within the model each vehicle is generated according to an exponential distribution with an interarrival time of at least two seconds (i.e., two seconds 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. For example, if it is assumed that the traffic stream is composed of ten percent trucks, the model randomly assigns truck characteristics to ten percent of the vehicles.

Vehicles enter the model a few hundred feet upstream of the lane drop sign. It is therefore assumed that vehicles are well informed of the upcoming lane closure. A small percentage of vehicles, however, remain on the terminating lane even after the posted lane drop sign. These vehicles, called late mergers, will merge as soon as they find adequate gaps in the traveling lane. Those vehicles that are not able to merge before the lane is terminated (where the barrels are located) must eventually stop and wait for the next acceptable gap. The waiting time for these vehicles is sometimes long because the through-lane vehicles are not modeled to recognize the vehicles in the terminating lane and provide them a gap. Vehicles in the through lane, however, respond to late mergers who merge immediately in front of them by adjusting their speed. The capacity impacts of the late mergers and other errant merging behavior are examined using simulation in a "before and after" study.

Drivers who join the queue at its end and wait to reach the head of the queue view those drivers who travel to the head of the queue in the terminating lane as "cheaters." Two truck drivers have been commonly observed to block cheaters by collaborating. One truck will travel in the through lane while another truck will travel side-by-side in the closed lane. When the two trucks reach the lane closure taper, the truck in the terminating lane will merge ahead of the truck in the through lane. Usually the two drivers travel slowly through the queue creating a significant gap between their trucks and the vehicle immediately downstream. This errant behavior will be evaluated using the simulation.

Given the traffic volume and the population of trucks and slow-moving vehicles, the simulation model estimates the expected travel time and speed throughout the modeled work zone. The model enables a traffic engineer to visually present the impact of a scheduled road construction to the public.

The model could also assist traffic engineers in rescheduling road construction if the estimated delay is unacceptable for the scheduled timeframe. A number of scenarios can be examined under various traffic conditions and designs to select the best plan before executing the actual construction activities.

The logic used by the simulation has been verified and the results have been validated by comparing the data collected in the field to those generated by the simulation. The validation procedure will be described in more detail later in the report.

## CAR-FOLLOWING ALGORITHM

The car-following theory is one of the most useful techniques for simulating vehicle interactions in a traffic flow. A driver constantly responds to the speed changes of the vehicle immediately downstream. He/she accelerates or decelerates as the lead vehicle speeds up or slows down. Car-following behavior has been formulated using differential equations by a number of researchers. These equations calculate a vehicle’s speed with respect to its distance from the front vehicle at a given time interval.

The traditional car-following theory represents space as a continuum and differential equations describe the relative position of vehicles with respect to one another. Microscopic simulation models, on the other hand, divide space into discrete positions. Car following is incorporated by updating the vehicles’ speed at designated points called stations. In our model, the stations are 100 feet apart. One hundred feet is believed to be a small enough increment of distance, at highway speeds, to closely model continuous space. In our examples, space intervals rather than time intervals are used to update vehicle assignments. The new car-following algorithm adjusts a vehicle's speed based on the headway (in feet) and the speed of the lead vehicle. Each vehicle upon its arrival is randomly assigned, among other attributes, a desired speed, which is the speed that each vehicle ultimately wishes to achieve.

Controlling vehicles based on space intervals (stations) rather than time is done to be consistent with the requirement of the simulation software used and has enabled us to take full advantage of Arena’s powerful animation module. Using Arena we are able to developing a high fidelity microscopic simulation model to be used as a visual medium for demonstration purposes. The development of such a model was the primary objective of this project.

A vehicle's desired speed is calculated by using Equation 1. The first term of the equation is the assigned work zone speed limit. The second term defines the additional amount of speed that a vehicle is willing to travel above the speed limit under safe conditions. The additional speed is assigned based on a driver's type. Table 1 includes the distribution of the desired speed above the work zone speed limit and the percentage of drivers desiring each increment.

$$v_d = v_{sign} + v_{over} \qquad (1)$$

*where*:

$v_d$ = vehicle's desired speed,
$v_{sign}$ = work zone speed limit, and
$v_{over}$ = speed above the speed limit.

**TABLE 1 Speed Over the Speed Limit** (5)

| Distribution of Drivers (%) | Speed Above Speed Limit (mph) |
|---|---|
| 5 | 0 |
| 25 | 5 |
| 45 | 10 |
| 20 | 15 |
| 5 | 20 |

When a vehicle arrives at the very first station in the simulation model, it detects the location and speed of the lead vehicle. It then accelerates or decelerates in response to the detected information based on the incorporated car-following algorithm. Once the vehicle reaches the next station, it again adjusts its speed relative to the lead vehicle's position and speed. This procedure will be repeated at every station throughout the network.

The car-following algorithm is triggered each time a vehicle enters a station. By detecting the location and speed of the lead vehicle, the car-following logic determines whether or not a vehicle may accelerate (to reach its desired speed) or decelerate. The logic begins by checking the vehicle's distance from its lead vehicle ($h$). It then compares the detected distance to two predetermined headways; $h_1$ and $h_2$. These two headways divide the car-following algorithm into three regimes. When the headway is less than $h_1$ (the first regime), the vehicle is following the lead vehicle closely and cannot travel any faster than the lead vehicle. The conditions for the first regime are expressed in Equation 2. Between headways $h_1$ and $h_2$, the following vehicle's speed is greater than the lead vehicle (the second regime) and the following vehicle may travel at a speed faster than the lead vehicle, but its acceleration is governed by the speed of the lead vehicle and the relative distance to the lead vehicle. The conditions for the second regime are expressed in Equation 3. When the headway with the lead vehicle is between $h_1$ and $h_2$ and its speed is greater than the lead vehicle or the headway is greater than $h_2$ (the third regime), the following vehicle is able to travel at its desired speed (free flow conditions). The conditions for the third regime are shown in Equation 4. Based on experimentation with the model, values of 100 feet (one station) and 300 feet (three stations) were selected for $h_1$ and $h_2$, respectively.

If $h \leq h_1$ then:

$$v = \min\{v_d, v_{lead}\} \qquad (2)$$

If $h_1 < h < h_2$ and $v \geq v_{lead}$ then:

$$v = v - \frac{v - v_{lead}}{(d_{lead} - d)/l} \qquad (3)$$

If ($h_1 < h < h_2$ and $v < v_{lead}$) or $h \geq h_2$ then:

$$v = \min\{v + \min[v_e, v/2], v_d\} \qquad (4)$$

*where*:

$v_d$ = vehicle's desired speed,
$v$ = vehicle's speed,
$v_{lead}$ = lead vehicle's speed,
$d$ = vehicle position,
$d_{lead}$ = lead vehicle position,
$l$ = distance between two stations (i.e., 100 ft),
$v_e$ = speed increment at a normal acceleration rate presented in Table 2.

Given the speed and vehicle type, the vehicle's allowable speed increment can be determined from Table 2. This table is adapted from the speed-distance relationships for the passenger cars, which represents acceleration rates of approximately 3.5 ft/sec$^2$ and less (i.e., normal acceleration rate) (6). For example, a car in the car-following regime, when allowed to accelerate and travel at 47 miles per hour (mph), may add 3 mph to its speed. The normal acceleration rates for trucks at each speed increment are assumed to be half the rates for passenger cars.

**TABLE 2 Passenger Car Speed Increments within a 100-ft Distance**

| Speed Range (mph) | Speed Increment, $v_e$ (mph) |
|---|---|
| 0 – 4 | 20 |
| 5 – 9 | 17 |
| 10 – 14 | 13 |
| 15 – 19 | 10 |
| 20 – 24 | 8 |
| 25 – 29 | 7 |
| 30 – 34 | 5 |
| 35 – 39 | 4 |
| 40 – 44 | 4 |
| 45 – 49 | 3 |
| +50 | 2 |

As an illustration of the car-following logic, assume that a vehicle, shown in a gray box in Figure 1, arrives at a station located at 1,200 ft ($d$) at the speed of 55 mph ($v$). Its desired speed ($v_d$), however, is 70 mph. It detects its lead vehicle, shown in a black box in Figure 1, at 1,400 ft ($d_{lead}$). Thus, the vehicle's distance from the lead vehicle ($h$) is 200 ft (i.e., 1400 - 1200).

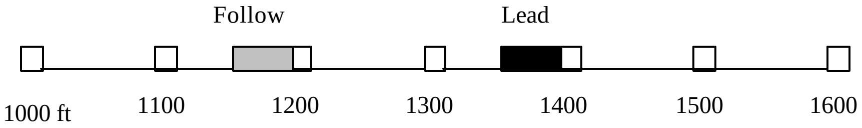


**FIGURE 1 A Car-Following Example**

Given the predetermined headways of $h_1$, $h_2$ as 100 and 300 feet, respectively, the detected distance falls in between the two headways ($h_1 < h < h_2$). Assuming the recorded lead vehicle's speed ($v_{lead}$) is 67 mph (i.e., $v < v_{lead}$), this case is in the car-following regime and Equation 4 will be used to update the vehicle's speed for the next 100 ft. The speed increment ($v_e$) at the current speed of 55 mph is obtained from Table 2 (i.e., 2 mph).

$$v = \min\{55 + \min[2, 55/2], 70\} = \min\{57, 70\} = 57 \text{ mph}$$

If instead of 67 mph, the lead vehicle's speed is 50 mph (i.e., $v \geq v_{lead}$), the decision-making will then fall into regime 2 and Equation 3 will be used to update the vehicle's speed for the next 100 ft.

$$v = 55 - \frac{55 - 50}{(1400 - 1200)/100} = 52.5 \text{ mph}$$

## LANE-CHANGING ALGORITHM

The lane-changing algorithm is another new component in the work zone simulation model. There are two types of lane-changing -- mandatory and discretionary. A mandatory lane-changing is when it becomes necessary for a vehicle to change lanes due to termination of one lane. A discretionary lane-changing is when a vehicle changes lanes to overtake a slower-moving vehicle or to allow an oncoming vehicle to merge. Changing lanes due to a lane closure at a work zone is an example of a mandatory lane-change.

Lane-changing is a complex driver behavior. The lane-changing logic in the model captures only the mandatory aspect of this behavior. Thus, only the vehicles on the terminating lane are modeled to change lanes. These vehicles will merge as soon as a sufficient gap in the traveling lane is found.

A vehicle that detects an adequate gap in the traveling lane immediately adjusts its speed with respect to the vehicle at the lead end of the gap by using Equation 5. A vehicle that, for example, is traveling 50 mph on the terminating lane reduces its speed when it verifies that the vehicle at the lead end of the detected gap is traveling at 45 mph. The vehicle at the follow end of the gap, however, adjusts its speed with respect to the lane-changing vehicle as soon as a lane-changing maneuver is initiated, adhering to the implemented car-following logic.

$$v_{lc} = \min\left\{v_{lc} + v_e, v_{glead}\right\} \tag{5}$$

*where*:

$v_{lc}$ = speed of a lane-changing vehicle,
$v_{glead}$ = speed of a vehicle at the lead end of a gap,
$v_e$ = speed increment at a normal acceleration rate presented in Table 2.

## MODEL VALIDATION

The model may provide results which are not always identical to the observed system. The purpose of model validation is to determine if the model replicates the actual system at an acceptable level of confidence (7). The simulation results are compared to the real system to validate the work zone simulation model.

Throughout the summer of 1998, traffic flow data were collected at the merge area of the case study work zone using video image processing technology. The merge area is the distance between the flashing arrow board and the bottleneck point where the construction starts (i.e., about 1,300 feet). Traffic flow data were retrieved by placing virtual detectors at desired points on the viewing areas of these video images. These data include traffic flow rate, speed, and headway at the two ends of the merge area. Given the vehicles' arrival and departure times, the travel time through the merge area was also obtained.

The field data indicate no substantial changes in the average speed at the merge area during the off-peak period. The average speed, however, significantly drops at the construction zone, as some drivers tend to reduce their speeds due to the lack of maneuverability.

Tables 3 through 5 present three days of field data. Each day includes 30 minutes of data where a sudden speed drop is observed at the merge area. A sudden speed drop indicates the transition from free flow to saturated condition and the development of a queue. The data are presented in five-minute intervals to capture the approximate time when saturation is reached and a speed drop occurs.

**TABLE 3 Field Data (2:40 PM – 3:05 PM) – June 19, 1998**

| Time | Volume (vph) | Average Speed (mph) | Average Headway (sec) | Travel Time (sec) | Queue Length (ft) |
|---|---|---|---|---|---|
| 14:40 | 100 | 64 | 3.0 | 20 | 0 |
| 14:45 | 109 | 62 | 2.8 | 15 | 0 |
| 14:50 | 124 | 55 | 2.4 | 44 | 0 |
| 14:55 | 107 | 30 | 2.8 | 87 | 0 |
| 15:00 | 102 | 16 | 3.0 | 73 | 1690 |
| 15:05 | 97 | 22 | 3.1 | 49 | 3696 |

**TABLE 4 Field Data (2:05 PM – 2:30 PM) – July 10, 1998**

| Time | Volume (vph) | Average Speed (mph) | Average Headway (sec) | Travel Time (sec) | Queue Length (ft) |
|---|---|---|---|---|---|
| 14:05 | 93 | 57 | 3.2 | 15 | 0 |
| 14:10 | 107 | 53 | 3.0 | 15 | 0 |
| 14:15 | 128 | 29 | 2.4 | 36 | 0 |
| 14:20 | 101 | 15 | 2.9 | 48 | 2482 |
| 14:25 | 102 | 16 | 3.0 | 45 | 4910 |
| 14:30 | 122 | 34 | 2.5 | 34 | 5808 |

**TABLE 5 Field Data (3:50 PM – 4:15 PM) – August 7, 1998**

| Time | Volume (vph) | Average Speed (mph) | Average Headway (sec) | Travel Time (sec) | Queue Length (ft) |
|---|---|---|---|---|---|
| 15:50 | 114 | 57 | na | na | 0 |
| 15:55 | 117 | 51 | 2.4 | 31 | 0 |
| 16:00 | 71 | 15 | 3.9 | 62 | 2746 |
| 16:05 | 101 | 19 | 2.8 | 49 | 5544 |
| 16:10 | 83 | 24 | 3.3 | 43 | 5386 |
| 16:15 | 109 | 33 | na | na | 6175 |

These field data are obtained under the traffic operating conditions presented in Table 6. Running the model under these traffic conditions enables us to examine the validity of the simulation results.

**TABLE 6 Field Traffic Operating Data on Different Days**

| Date | Traveling Lane Utilization | | Traffic Volume (vph) | Percent of Trucks |
|---|---|---|---|---|
| | % Cars | % Trucks | | |
| 6/19/98 | 2 | 1 | 1488 | 25 |
| 7/10/98 | 1 | 0 | 1536 | 25 |
| 8/7/98 | 2 | 0 | 1404 | 25 |

Tables 7 through 9 compare the field data to the simulation results. The field volume, average speed, travel time, and average headway are shown for three days under the columns labeled "Fld." For the same simulated days, the results are shown in the columns next to the field data, and a 95 percent confidence interval (CI) for the simulation results is also noted. The confidence intervals provide lower and upper limits of the true simulation point estimate of averages. For example, it can be stated with 95 percent confidence that the true average speed at 16:05 on August 7, 1998 was between 19 and 21 mph. The actual average speed from the field data is 20 mph.

**TABLE 7 Field and Simulation Results – June 19, 1998**

| Time | Volume (vph) | | | Avg Speed (mph) | | | Travel Time (sec) | | | Avg Headway (sec) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Fld | Model | | Fld | Model | | Fld | Model | | Fld | Model | |
| | Avg | Avg | CI | Avg | Avg | CI | Avg | Avg | CI | Avg | Avg | CI |
| 14:40 | 100 | 128 | 123,133 | 64 | 62 | 61,63 | 20 | 17 | 15,19 | 3.0 | 2.4 | 2.3,2.5 |
| 14:45 | 109 | 125 | 120,130 | 62 | 61 | 60,62 | 15 | 22 | 19,25 | 2.8 | 2.4 | 2.3,2.5 |
| 14:50 | 124 | 113 | 109,117 | 55 | 60 | 58,62 | 44 | 27 | 23,31 | 2.4 | 2.7 | 2.6,2.8 |
| 14:55 | 107 | 100 | 96,104 | 30 | 34 | 32,34 | 87 | 29 | 27,31 | 2.8 | 3.0 | 2.9,3.1 |
| 15:00 | 102 | 58 | 56,60 | 16 | 17 | 16,18 | 73 | 64 | 62,66 | 3.0 | 5.2 | 5.1,5.3 |
| 15:05 | 97 | 97 | 96,98 | 22 | 24 | 23,25 | 49 | 39 | 38,40 | 3.1 | 3.1 | 3.0,3.2 |

**TABLE 8 Field and Simulation Results – July 10, 1998**

| Time | Volume (vph) | | | Avg Speed (mph) | | | Travel Time (sec) | | | Avg Headway (sec) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Fld | Model | | Fld | Model | | Fld | Model | | Fld | Model | |
| | Avg | Avg | CI | Avg | Avg | CI | Avg | Avg | CI | Avg | Avg | CI |
| 14:05 | 93 | 131 | 126,136 | 57 | 57 | 56,58 | 15 | 17 | 16,18 | 3.2 | 2.3 | 2.2,2.4 |
| 14:10 | 107 | 122 | 117,127 | 54 | 56 | 55,57 | 15 | 18 | 17,19 | 3.0 | 2.5 | 2.4,2.6 |
| 14:15 | 128 | 101 | 98,104 | 29 | 29 | 28,30 | 36 | 31 | 30,32 | 2.4 | 3.0 | 2.9,3.1 |
| 14:20 | 101 | 56 | 55,57 | 15 | 16 | 15,17 | 48 | 67 | 66,68 | 2.9 | 5.4 | 5.3,5.5 |
| 14:25 | 102 | 57 | 56,58 | 16 | 16 | 25,17 | 45 | 66 | 66,68 | 3.0 | 5.3 | 5.2,5.4 |
| 14:30 | 122 | 140 | 139,141 | 34 | 35 | 34,36 | 34 | 27 | 26,28 | 2.5 | 2.1 | 2.0,2.1 |

**TABLE 9 Field and Simulation Results – August 7, 1998**

| Time | Volume (vph) | | | Avg Speed (mph) | | | Travel Time (sec) | | | Avg Headway (sec) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Fld | Model | | Fld | Model | | Fld | Model | | Fld | Model | |
| | Avg | Avg | CI | Avg | Avg | CI | Avg | Avg | CI | Avg | Avg | CI |
| 15:50 | 114 | 114 | 108,120 | 57 | 56 | 55,57 | na | 19 | 18,20 | na | 2.7 | 2.5,2.8 |
| 15:55 | 117 | 108 | 103,113 | 51 | 53 | 52,54 | 31 | 25 | 22,28 | 2.4 | 2.8 | 2.7,2.9 |
| 16:00 | 71 | 56 | 55,57 | 15 | 16 | 15,17 | 62 | 60 | 59,61 | 3.9 | 5.4 | 5.3,5.5 |
| 16:05 | 101 | 71 | 70,72 | 19 | 20 | 19,21 | 49 | 54 | 53,55 | 2.8 | 4.3 | 4.2,4.4 |
| 16:10 | 83 | 91 | 90,92 | 24 | 25 | 24,26 | 43 | 42 | 41,43 | 3.3 | 3.3 | 3.2,3.4 |
| 16:15 | 109 | 127 | 126,128 | 33 | 30 | 30,30 | na | 29 | 29,29 | na | 2.4 | 2.4,2.4 |

Figures 2 through 13 graphically compare the field and simulation results. These figures are indicative of the model's capabilities to simulate traffic operations at the case study work zone. Results provided by the model are close to the field data and, when discrepancies occur, follow the field data trend.

The relationship between the speed, headway, and volume indicates that as the speed decreases the headway becomes longer and, as a result, the volume declines. The simulation model ideally responds to this relationship by decreasing the traffic volume and increasing the headway as the speed drops. The field data, however, show a more moderate response to the same speed drop. For instance, the field data on June 19, 1998 indicate only two-tenths of a second increase in the average headway during the 3:00 PM period when the average speed drops from 30 mph to 16 mph (see Figures 3 and 5). The model, on the other hand, responds to this speed drop by increasing the average headway by 2.2 seconds. Moreover, as shown in Figure 4, the traffic volume inversely responds to the same speed drop by decreasing volume in proportion to the longer headways.

The field data also indicate that the travel time through the merge area increases as the speed recorded at the flashing arrow board decreases. In other words, vehicles seem to travel through the merge area at about the initial speeds recorded at the flashing board. There is, however, some evidence that vehicles seem to react to downstream traffic movements by speeding up or slowing down while still traveling through the merge area. These speed changes result in lower or higher travel times with respect to the speeds initially recorded at the flashing board.

Assuming no drastic changes in the speed throughout the merge area, the model is able to replicate the observed average travel times at a number of time periods (see Figure 12). The discrepancies between the field and the model's average travel times during the 2:20 PM and 2:25 PM periods on July 10, 1998 (see Figure 8) are the result of speeding up through the merge area. Furthermore, the dissimilarities between the average travel times during the 2:55 PM and 3:00 PM periods on June 19, 1998 (see Figure 4) are a result of slowing down through the merge area.

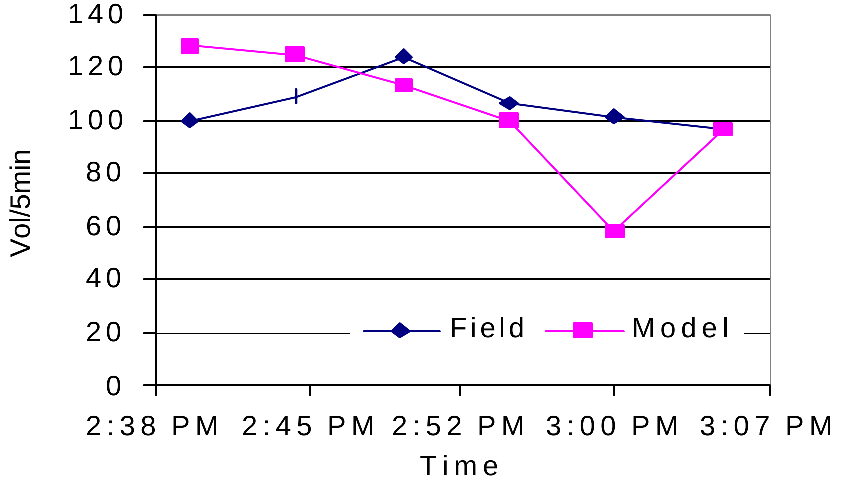


**FIGURE 2 Traffic Count at Flashing Arrow Board – June 19, 1998**

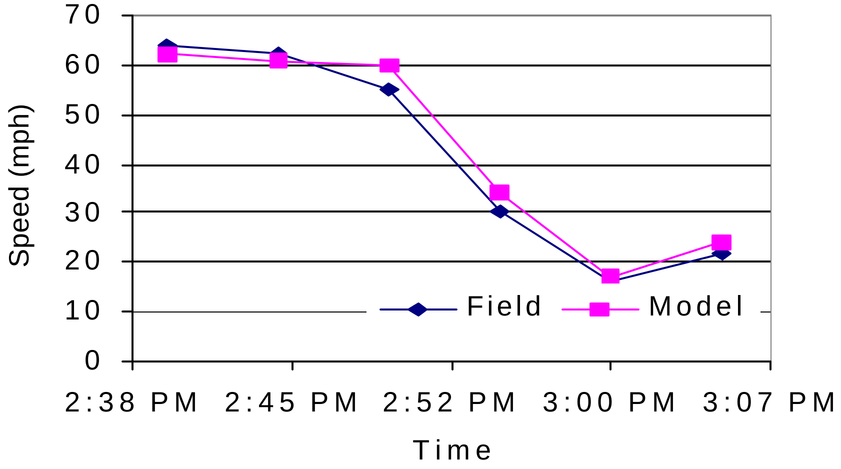


**FIGURE 3 Average Speed at Flashing Arrow Board – June 19, 1998**

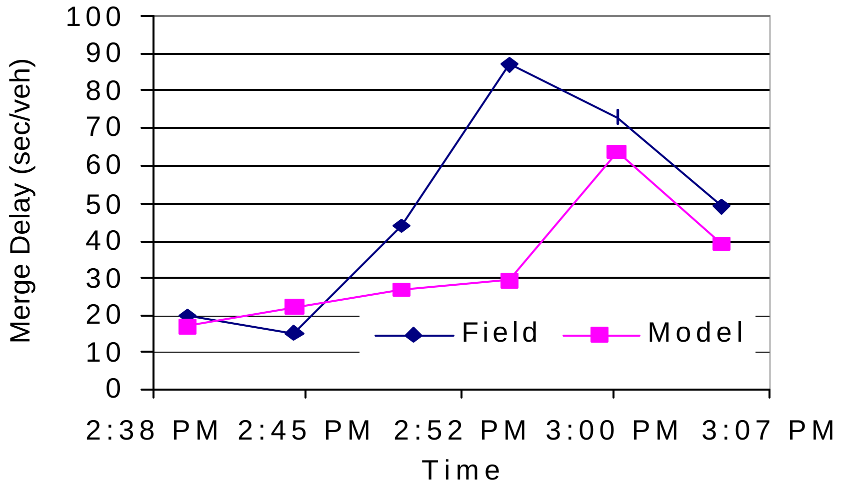


FIGURE 4  Merge Area Average Travel Time – June 19, 1998

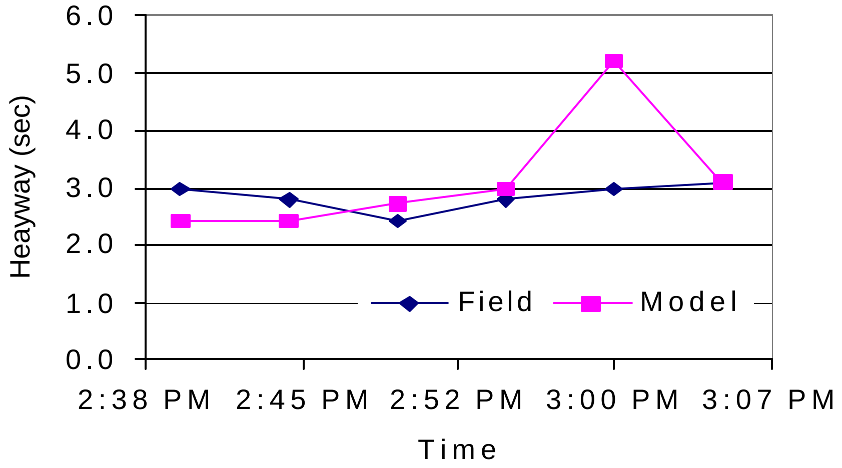


FIGURE 5  Average Headway at Flashing Arrow Board – June 19, 1998

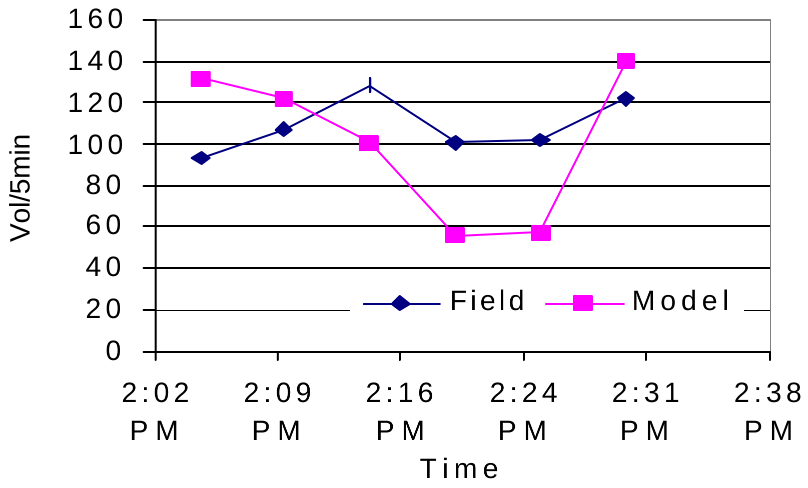


**FIGURE 6 Traffic Count at Flashing Arrow Board – July 10, 1998**

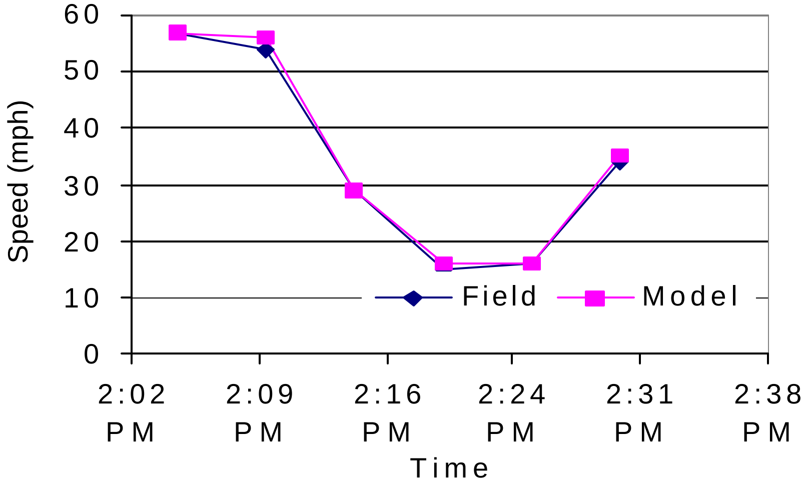


**FIGURE 7 Average Speed at Flashing Arrow Board – July 10, 1998**

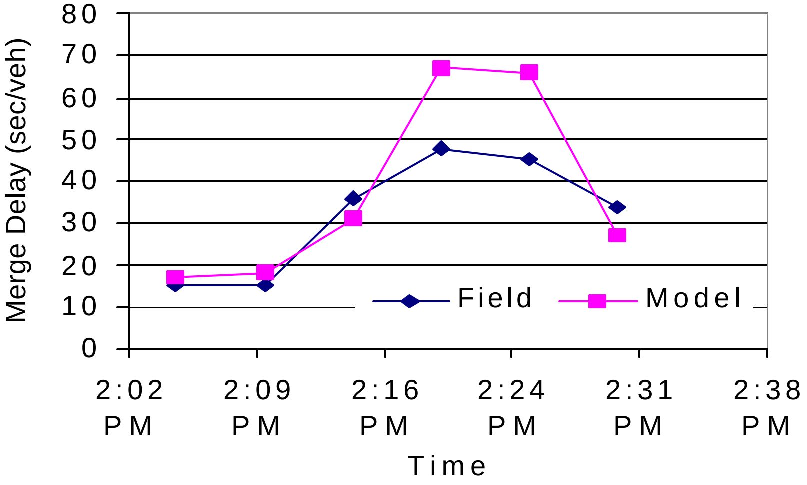


FIGURE 8  Merge Area Average Travel Time – July 10, 1998

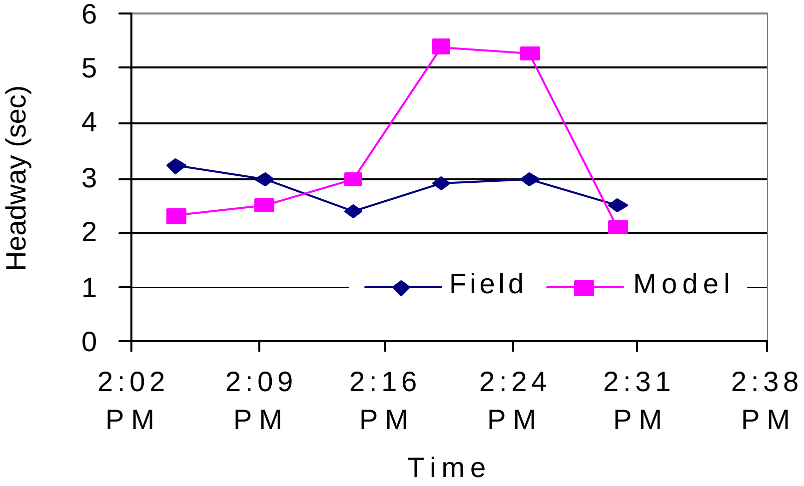


FIGURE 9  Average Headway at Flashing Arrow Board – July 10, 1998

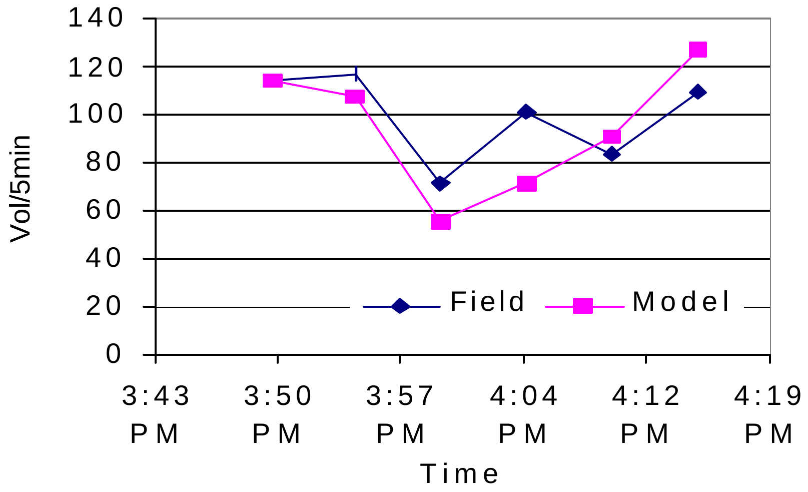


FIGURE 10 Traffic Count at Flashing Arrow Board – August 7, 1998

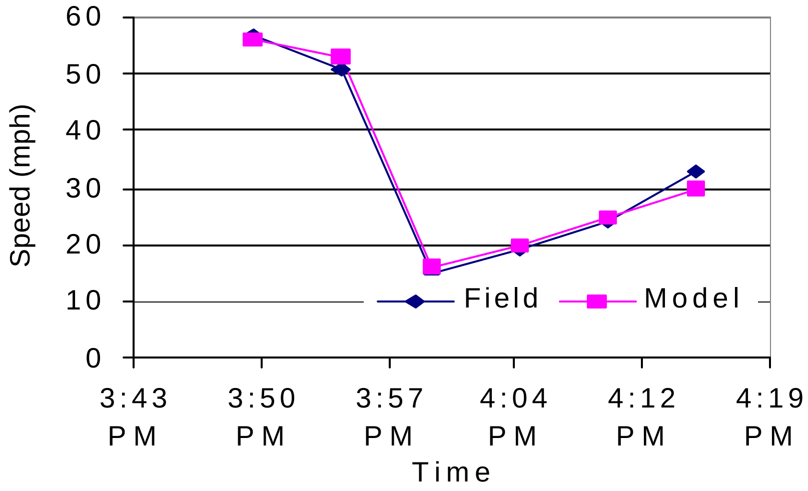


FIGURE 11 Average Speed at Flashing Arrow Board – August 7, 1998

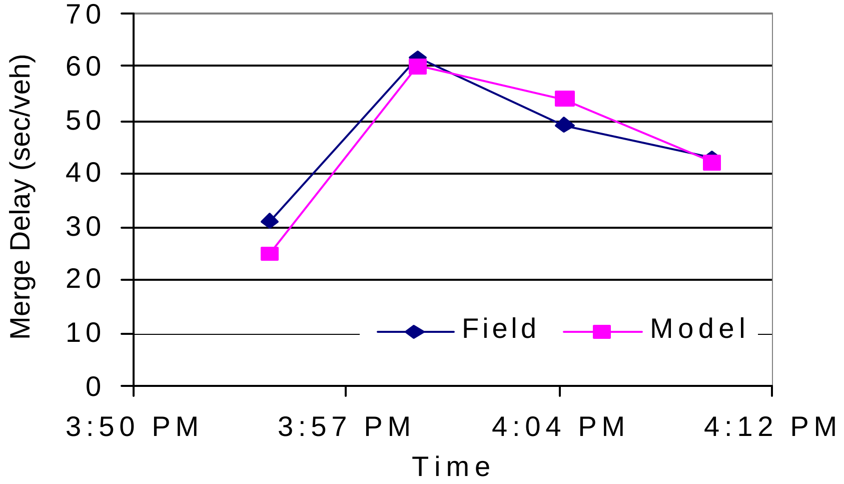


**FIGURE 12 Merge Area Average Travel Time – August 7 , 1998**

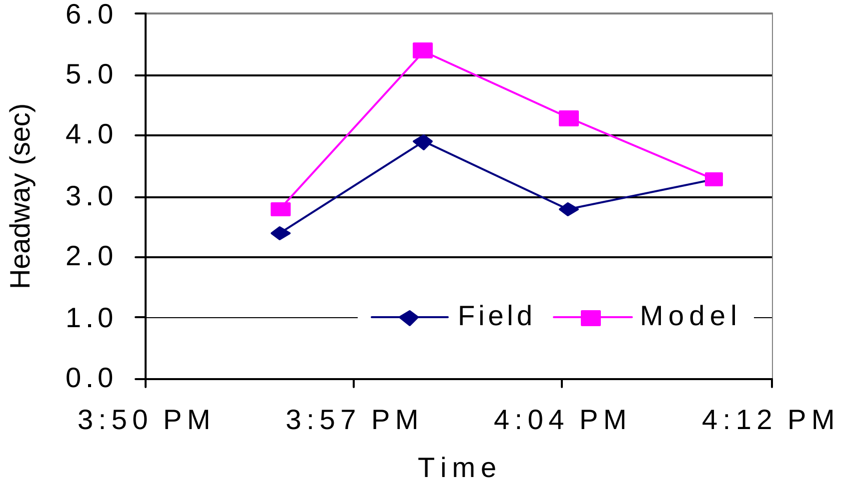


**FIGURE 13 Average Headway at Flashing Arrow Board – August 7, 1998**

Comparison of the field data with the model's outputs establishes a level of confidence that the model is capable of simulating the existing conditions of the case study work zone. Confidence in the model yields a similar level of confidence in the model outputs obtained under other traffic conditions. These comparisons also indicate the need for the model's enhancement, which could be accomplished by improving the implemented car-following and lane-changing logic and conducting additional experiments.

## EXPERIMENTS WITH 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 called the Indiana Lane Merge System (ILMS). A drawing of the concept is shown in Figure 14 (8). The ILMS creates a variable no-pass zone in the terminating lane. In other words, immediately upstream from the merge taper are static signs stating, "DO NOT PASS," and one sign with flashing strobe lights (sign one in Figure 14) stating, "WORKSITE DO NOT PASS WHEN FLASHING." Thus, the first four signs create a static no-pass zone. The signs upstream are significant 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 then activates sign two, and so on, until all signs are activated. This creates a dynamic no-pass zone.

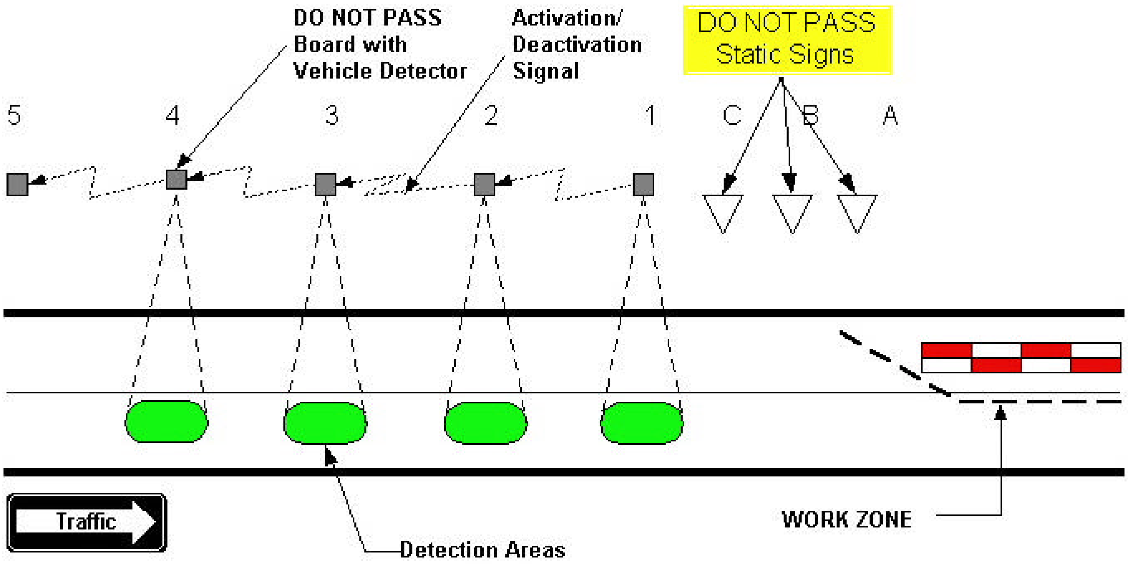


FIGURE 14 Conceptual Drawing of Indiana Lane Merge System[8]

To evaluate the dynamic no-pass zone, we modified the simulation so that the moment 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 15 and demonstrate a modest increase in average speed (about a five-mile per hour increase in speed) and a reduction in the average travel times (a 12-second reduction).

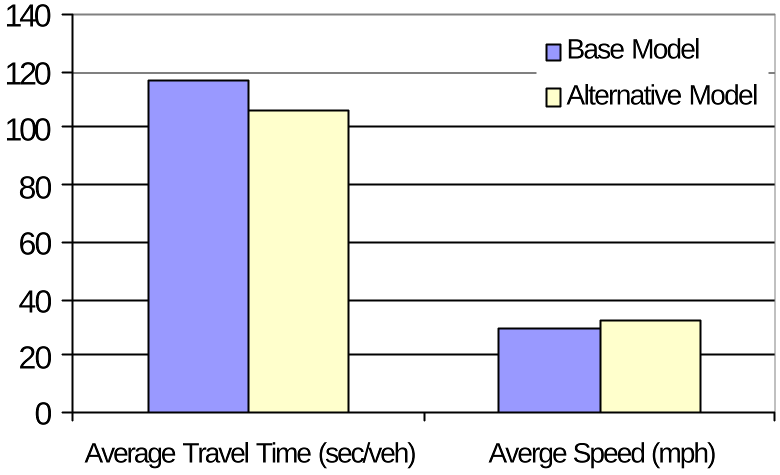


**FIGURE 15 Comparison of Dynamic No Pass Zone versus Base Case**

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 work zones; the improvement, however, is modest. Only limited field-testing has been done, and it illustrated that because drivers were unfamiliar with the system, the resulting 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 preceding them. To illustrate the impact of trucks traveling side-by-side in both lanes, when a slow moving truck is generated by the model a tandem vehicle is also generated in the terminating lane. The two vehicles move 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 (measured by 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.

## CASE STUDY

The work zone simulation model is developed for a conventional work zone with a two-to-one configuration (i.e., two lanes reduced to a single lane). Given the traffic flow rates, the model enables traffic engineers to predict expected delays at work zones with similar design configurations during construction days. This section of the report examines the model's capabilities in estimating the average travel time and speed at a work zone with a two-to-one configuration in Williamsburg, Iowa, for the entire day of July 20, 1997. The traffic profile of the day is presented in the second column of Table 10.

Using the 24-hour traffic profile, the model is run under the following assumptions:

- Truck population: 25 percent,
- Speed limit: 55 mph,
- Slow moving cars: one percent traveling at 45 mph, and
- Slow moving trucks: three percent traveling at 25 mph.

The model determines the average travel time and speed throughout the corridor and the merge area for each hour of the day. Table 10 includes the simulation results. Using the results, the speed-flow relationship at the corridor as well as the merge area can be determined.

Using the actual traffic volume distribution from the Williamsburg site, it is clear that the traffic flow condition in the merge area begins to decay when the traffic volume reaches 583 vehicles per hour (vph). At 9:00 am the volume reaches 583 vph and the average speed at the merge point declines to 33 mph. Figure 16 calculates the average speed over the approach corridor and the average speed at the merge point against volume. When volume exceeds 583 vph, the average speed at the merge point drops far below the average speed throughout the entire corridor. The difference is the result of the shock waves created by late-merging vehicles and passive drivers.

**TABLE 10  Average Travel Time/Speed, Williamsburg Work Zone,  July 20, 1997**

| Time | Volume (vph) | Corridor | | Merge Area | |
|---|---|---|---|---|---|
| | | Travel Time (s/veh) | Speed (mph) | Trv Time (s/veh) | Spd (mph) |
| 12:00 AM | 342 | 53 | 64 | 14 | 63 |
| 1:00 AM | 257 | 53 | 64 | 14 | 63 |
| 2:00 AM | 249 | 53 | 64 | 14 | 63 |
| 3:00 AM | 161 | 53 | 65 | 13 | 63 |
| 4:00 AM | 111 | 53 | 65 | 14 | 64 |
| 5:00 AM | 129 | 53 | 65 | 13 | 63 |
| 6:00 AM | 182 | 53 | 65 | 13 | 63 |
| 7:00 AM | 227 | 53 | 64 | 14 | 63 |
| 8:00 AM | 385 | 55 | 63 | 14 | 60 |
| 9:00 AM | 583 | 64 | 53 | 26 | 33 |
| 10:00 AM | 779 | 64 | 53 | 24 | 36 |
| 11:00 AM | 986 | 71 | 48 | 26 | 33 |
| 12:00 PM | 1184 | 70 | 49 | 35 | 24 |
| 1:00 PM | 1170 | 74 | 46 | 32 | 27 |
| 2:00 PM | 1257 | 77 | 44 | 45 | 19 |
| 3:00 PM | 1404 | 87 | 39 | 57 | 15 |
| 4:00 PM | 1348 | 81 | 42 | 40 | 21 |
| 5:00 PM | 1265 | 72 | 47 | 38 | 22 |
| 6:00 PM | 1206 | 75 | 45 | 44 | 19 |
| 7:00 PM | 1301 | 74 | 46 | 41 | 21 |
| 8:00 PM | 1253 | 74 | 46 | 45 | 19 |
| 9:00 PM | 1095 | 75 | 45 | 25 | 34 |
| 10:00 PM | 692 | 64 | 54 | 26 | 33 |
| 11:00 PM | 567 | 62 | 55 | 34 | 25 |

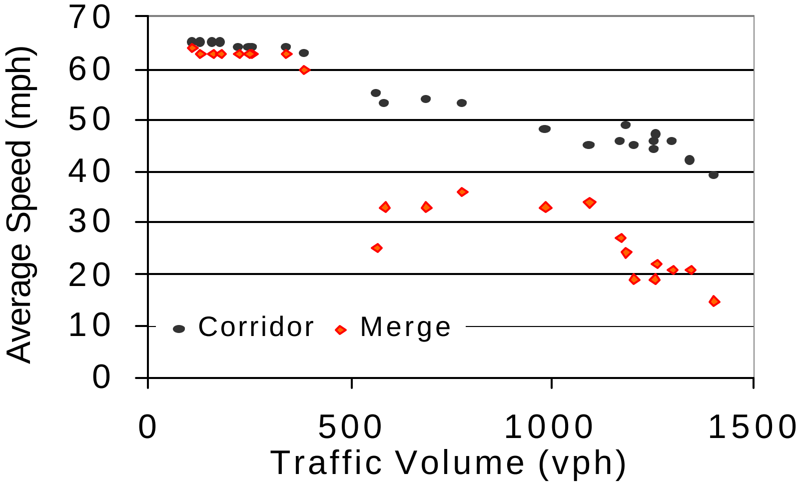


**FIGURE 16 Speed-Flow Relationships for Modeled Williamsburg Work Zone**

## TOTAL DELAY

The model also calculates the total delay of all vehicles entering the system. The delay estimates are based on the difference in travel speed between free-flow conditions and the conditions being modeled. The delay in the approach corridor is based on the average travel times simulated by the computer program, which takes into account the interactions between vehicles. However, upstream of the merge corridor, the model simply uses deterministic queuing (for an explanation of deterministic queuing see the companion report (9)). Although we believe that the model's estimate of delay upstream of the approach corridor is reasonable for practical purposes, it will underestimate the delay.

To illustrate the impact of congestion on total delay, total delay was calculated for traffic volumes ranging from 400 vph to 2,100 vph. The results are shown in Figure 17 and the total delay is calculated for one simulated hour. Total delay begins to build slowly at 700 vph up to 1,450 vph. As the traffic volumes increase past 1,450 vph, delay builds precipitously. For example, at 1,500 vph the total delay is 1,134 minutes and at 1,700 vph the total delay is more than four times greater than at 4,751 minutes. Because the run time version of the simulation only simulates one hour, many of the vehicles, which entered the system during the simulation, are still in the simulation when it concludes. The simulation also has a facility which estimates how long it takes the last vehicle to enter the queue at the end of the simulation to reach the merge point. For 1,500 vph, the last vehicle clears the merge point in 78 seconds; with 1,700 vph, the last vehicle created clears the merge point in 279 seconds.

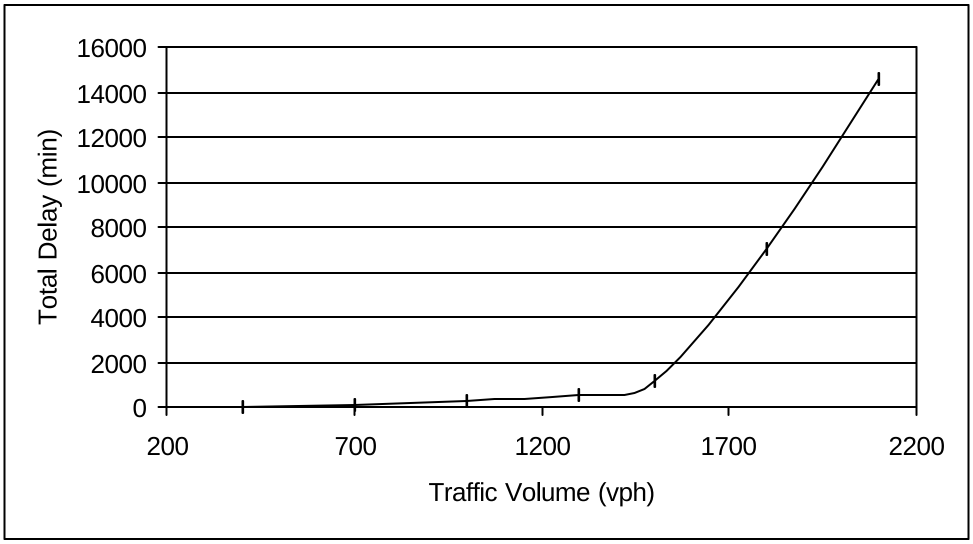


**FIGURE 17 Total Delay for Different Traffic Volumes**

## CONCLUDING REMARKS

Arena provides a modeling framework for building models across a wide range of applications. Being a general-purpose modeling tool, Arena has enabled us to model traffic operations at work zones, which require dynamic assignment of characteristics to each vehicle.

The work zone simulation model was developed to examine the impact that slow-moving vehicles and late mergers have on average speed and delay. The model determines the average travel time and speed throughout the case study work zone and enables the evaluation of traffic control strategies.

The model is also capable of estimating the length, delay, and dissipation time of the resulting queue. However, comparison of field data to the simulation results indicates that the model overestimates the queue length. It was therefore determined not to include the queue length estimates in the model, although the model does estimate total delay.

The queue overestimation is the result of the model's limited capacity. The model does not take into account the lane distribution long distances upstream from the merge approach corridor. In the actual system, vehicles are distributed across both lanes but the model assumes that most (97 percent) are in the through lane. Therefore, the model typically overestimates the length of the queue. Further model enhancements and additional data collection would allow for more accurate estimates of queue length.

A clear understanding of how much delay will occur prior to executing actual construction activities benefits traffic engineers in their traffic management strategies during the construction period.  The work zone simulation model is a tool that enables a traffic engineer to estimate delays at a scheduled work zone under forecasted traffic conditions.

# PART II Work Zone Simulation Model User's Manual

## INTRODUCTION

The work zone simulation model was developed based on the existing geometry and traffic patterns of a work zone with a two-to-one configuration. The model simulates traffic operations upstream and through a work zone. It is assumed that vehicle operators are informed of the upcoming lane closure. In response, most vehicles have merged onto the through lane prior to reaching the posted lane drop sign. There are, however, a small number of vehicles (e.g., about three percent) that remain on the terminating lane seeking adequate gaps to merge. A vehicle that is not able to merge before the lane is terminated will eventually stop at the beginning of the merge taper and wait for the next available gap. The simulation results indicate that this small number of late-merging vehicles substantially reduces the average speed of vehicles in the through lane.

The model is capable of examining the impact of these late mergers and other slow-moving vehicles at the average traffic speed under user-defined traffic stream characteristics. Its high fidelity animation also allows a traffic engineer to illustrate traffic behavior in a work zone and the resulting impact to a general audience. With the ability to modify parameters within the model, the traffic engineer can examine a number of scenarios before finalizing a road construction traffic management plan.

The work zone simulation is a microscopic model with a powerful animation capability. The model is built in Arena simulation software (10). The "Pack and Go" feature of Arena enables the end users to view the model's animation and outputs using Arena Viewer software. This software runs the "packed" model on any personal computer running Windows 95 or NT 4.0.

This manual has been developed to assist users in the setup and operation of the work zone simulation model. No prior computer programming skills are required to use the model.

## INSTALLATION

Arena Viewer software runs the work zone simulation model on the Windows 95 platform. It is provided in eight diskettes that have been transferred to a CD. Insert the CD into the disk drive and, using the Windows *Start/Run* command, run the *drive name:*\viewer\setup program. Follow the instructions on the screen.

To run Arena Viewer, select the Windows' *Start/Programs/Arena Viewer* menu command. Figure 18 shows the first screen after Arena Viewer is opened. This is the basic Arena Viewer window, which consists of a menu bar and toolbars at the top and a status bar along the bottom. The icons, included in toolbars, are shortcuts for main menu commands. Placing the mouse cursor over an icon highlights its function. The status bar provides a brief description of the specific function currently being performed.

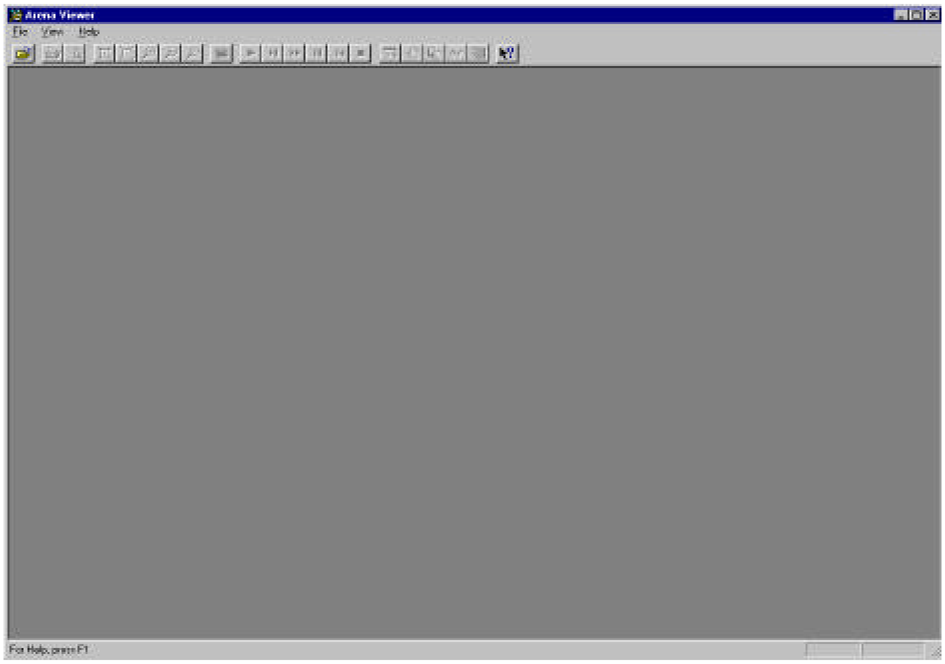


**FIGURE 18 Arena Viewer Basic Window and Toolbars**

## GETTING STARTED

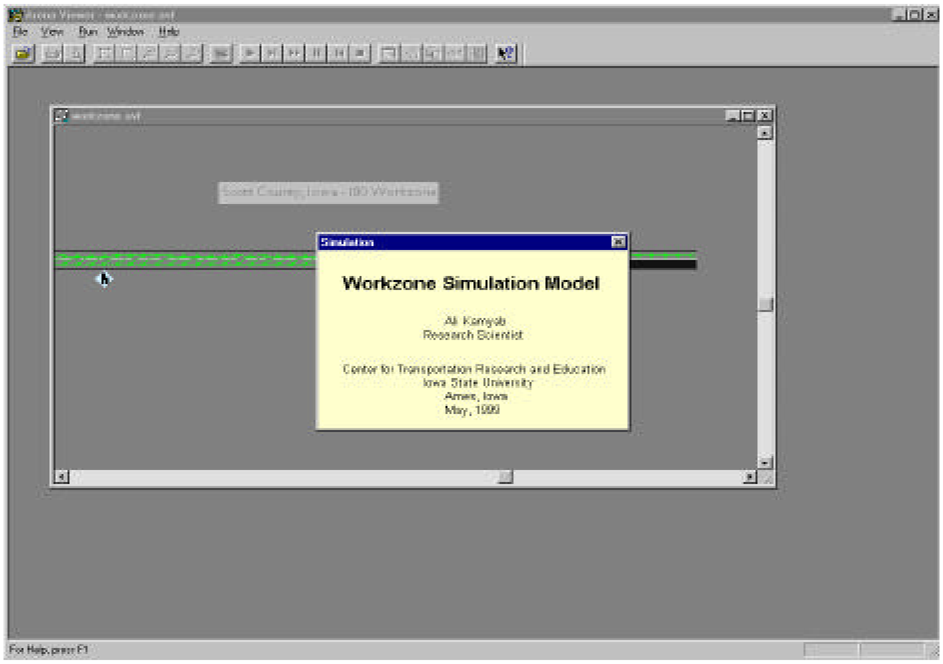
The work zone simulation model consists of two files -- an *avf* file containing the animation portion of the model and the program (*p*) file containing data. These two files together (saved in the same folder) enable the Arena Viewer to animate the model and calculate the output results.

To run the simulation model, the following steps should be taken:

1. Click on *File/Open* from Arena Viewer's main menu (or use the Open toolbar button).
2. Double-click on the folder containing the two simulation files.
3. Select *workzone.avf*.
4. Click the Open button.

Figure 19 shows the first screen after the model opens. The simulation title page will close after two seconds.

5. Maximize the opened simulation window.
6. Press the shortcut key "z" (will be explained in Table 13) to zoom out the entire work zone in the opened window.
7. Click the Go button on the Run toolbar to start the simulation run.



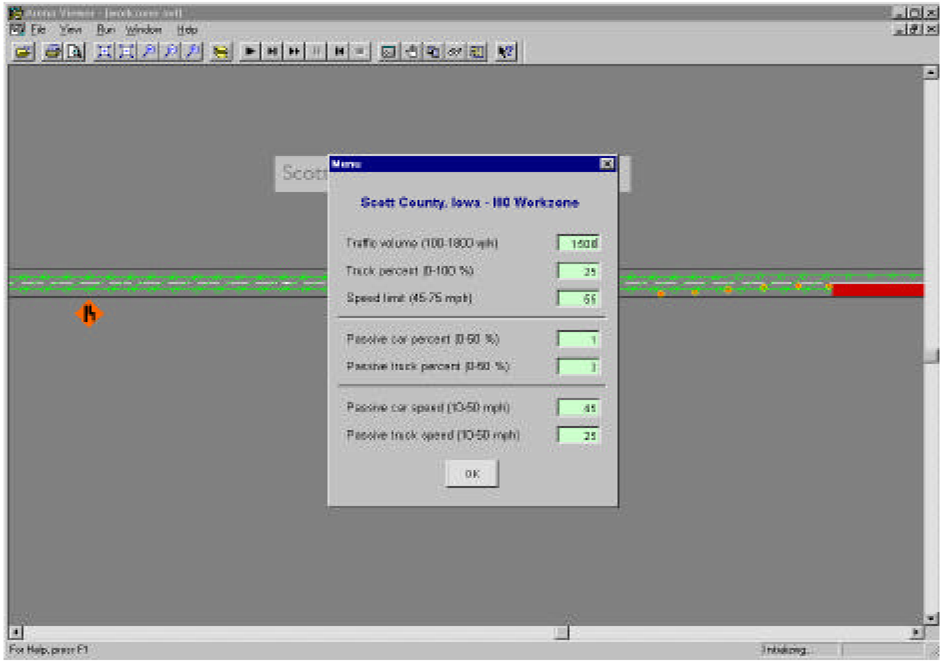
Workzone Simulation Model

Ali Kamyab
Research Scientist

Center for Transportation Research and Education
Iowa State University
Ames, Iowa
May, 1999

**FIGURE 19 Simulation Title Page**

As soon as the Go button is clicked, users are presented with a menu, shown in Figure 20. This menu allows users to change the default values of the model's parameters, within the specified limits, before starting a run. Click the OK button to start the simulation run or change any of the parameters before clicking the OK button to run a new scenario.



Scott County, Iowa - I80 Workzone

Traffic volume (100-1800 vph) 1500
Truck percent (0-100 %) 25
Speed limit (45-75 mph) 65
Passive car percent (0-50 %) 1
Passive truck percent (0-50 %) 1
Passive car speed (10-50 mph) 45
Passive truck speed (10-50 mph) 25

FIGURE 20  Simulation Model Menu

The status of each simulated vehicle is represented by its assigned color in the model. For example, a yellow colored vehicle is a passive vehicle. A complete list of the assigned colors is included in Table 11.

TABLE 11  Colors of Animated Vehicles

| Color | Assignment |
|---|---|
| White | Active vehicles |
| Yellow | Passive vehicles |
| Blue | Lane changed vehicles |

Tables 12 and 13 include shortcut keys that can be used while the simulation model is running. The shortcut keys, listed in Table 12, can be used to interrupt the simulation run or change the animation speed. For example, in order to interrupt the model execution before the end of the simulation press the Esc key, or click the Pause button on the Run toolbar. To resume the simulation, click the Go button again.

**TABLE 12 Arena Viewer Shortcut Keys**

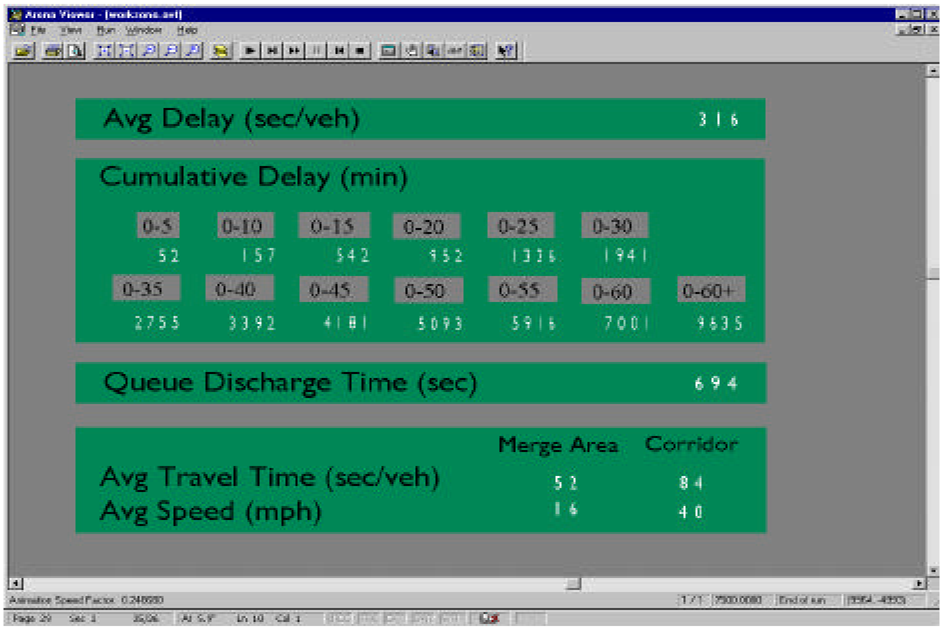
| Key | Function |
|---|---|
| Esc | Interrupt or pause the simulation |
| + or - | Zoom in or out from the current view |
| Arrow keys | Pan from the current view |
| < | Slow down the animation |
| > | Speed up the animation |

The keys included in Table 13 are specific to the work zone model. These keys automatically zoom and pan to a specific view. Note that these keys are case sensitive.

**TABLE 13 Work zone Simulation Model Shortcut Keys**

| Key | View |
|---|---|
| z | Work zone zoom out |
| d | Posted drop lane sign |
| m | Merge area |
| o | Results summary |

When the model run is complete, a dialog box appears asking whether the user would like to view the results. Click No to close the dialog box since these data are unlikely to be of much use in the presented form. A likely more useful summary of the results can be viewed by pressing the shortcut key "o" anytime during or after the simulation run before exiting the Run mode. Figure 21 shows a summary of the results during a simulation run. The run shown in Figure 21 assumes a traffic volume of 1,800 vehicles per hour, with the flow consisting of 25 percent trucks, a speed limit of 55, one percent passive automobile drivers, and three percent passive truck drivers.



Avg Delay (sec/veh) 316

Cumulative Delay (min)

| 0-5 | 0-10 | 0-15 | 0-20 | 0-25 | 0-30 | |
|---|---|---|---|---|---|---|
| 52 | 157 | 542 | 952 | 1336 | 1941 | |
| **0-35** | **0-40** | **0-45** | **0-50** | **0-55** | **0-60** | **0-60+** |
| 2755 | 3392 | 4181 | 5093 | 5916 | 7001 | 9635 |

Queue Discharge Time (sec) 694

| | Merge Area | Corridor |
|---|---|---|
| Avg Travel Time (sec/veh) | 52 | 84 |
| Avg Speed (mph) | 16 | 40 |

**FIGURE 21 Simulation Sample Output**

The model calculates delay by comparing the free flow travel time with the travel time of each simulated vehicle. The average delay time is reported at the top of the screen, and it is the average delay over the entire simulated hour. The cumulative delay is the total delay experienced by all vehicles reported in five-minute increments. The last cumulative delay interval is 0-60+, and that is the cumulative delay until the last vehicle to enter the queue at the end of the 60-minute simulation reaches the merge point. In Figure 21, the total delay incurred by all of the vehicles created during the 60-minute experiment is 9,635 minutes (about 160 hours). The queue discharge time is the time required for the last vehicle to enter the queue at the end of the one-hour simulation to reach the head of the queue, in this case 694 seconds (almost 12 minutes). The corridor is the entire traveling length of the modeled work zone (i.e., about 5,000 ft). The merge area is the distance between the flashing arrow board and the bottleneck point where the construction starts (i.e., about 1,300 ft). Click the End button on the Run toolbar to exit the Run mode.

The cumulative delay time for runs made with traffic volumes of 1,600, 1,800, and 2,000 vph are shown in Figure 22. Note that the delay increases as the time interval increases. In addition, the cumulative delay increases at a much faster rate than the traffic volume. For example, the total cumulative delay for the enter period simulated is five times greater when the traffic volume is 2,000 vph than it is when it is 1,600 vph.

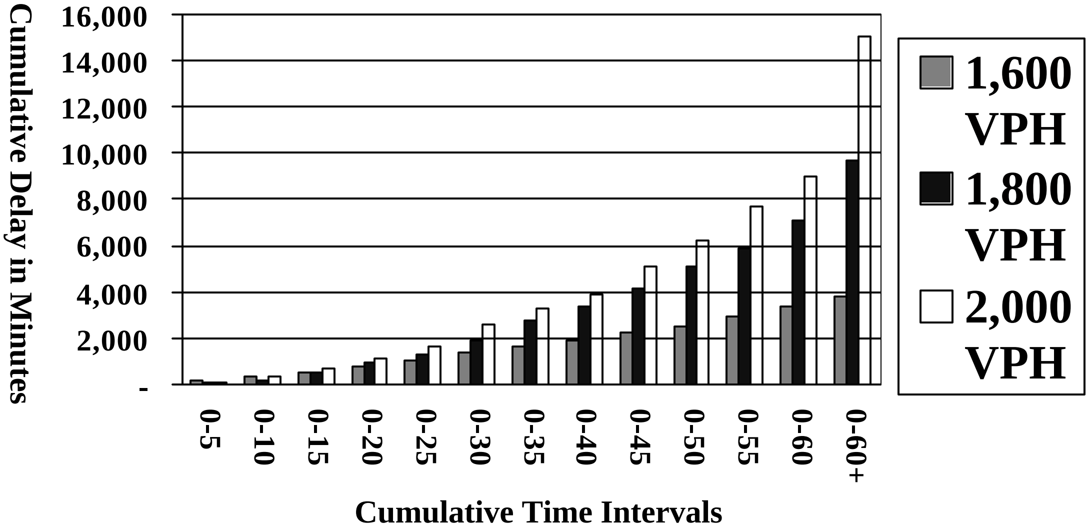


**FIGURE 22 Cumulative Delay Times**

The average CPU time for a one-hour run is about 15 minutes on a Pentium computer. The running time can be reduced to four minutes by disengaging the model's animation. This can be done by clicking the Fast-Forward button on the Run toolbar, instead of the Go button, and minimizing the Viewer window.

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