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A SIMULATION STUDY OF TRAFFIC CONTROL PROCEDURES AT HIGHWAY WORK ZONES

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ABSTRACT

Construction zones often cause considerable inconveniences in highway traffic. They are often in the form of the closure of one or more lanes. Two major effects of these lane closures are traffic delays and safety hazards to drivers. The objective of this research is to study the traffic behavior at freeway work zones and come up with recommendations for the control procedures at such sites. This goal has been accomplished through completion of two tasks: 1) Development of a microscopic traffic simulation model to reflect the actual traffic flow patterns at and upstream from the construction site. 2) Validation of the model by means of data collection and comparison of the results with those of the model for a number of different traffic volumes. The data was used not only to test the microscopic traffic behavior, but the macroscopic as well, and in both cases the results were satisfactory. The model was then used as a means of experimentation to reach an optimum location for a control sign to result in the minimum traffic delay.

1 INTRODUCTION

With the ever increasing traffic volumes on the highway systems nationwide, it becomes more important to consider the impact of construction projects on the efficiency and safety of highways. By far, the most common traffic control procedure utilized at construction zones is the closure of one or more (but not all) lanes to traffic while the construction activity is underway. From an operational standpoint, the created bottleneck results in a sharp reduction in operating speeds, especially when the observed traffic volumes are close to the bottleneck capacity. Moreover, the additional maneuvering required to proceed safely through the construction zones, i.e., safe car following and lane changing present a challenge that may not be met successfully by all drivers.

The Institute of Transportation Engineers has set forth specific guidelines for the installation of traffic control devices at construction zones as an integral part of the Manual on Uniform Traffic Control Devices (1978). These minimum requirements however, fall short of being adapted to the high variation in site conditions from one construction project to the other. It is therefore necessary to focus on optimizing traffic control procedures at lane closures on divided highways.

A prerequisite to the experimentation of various traffic control configurations is the presence of a stochastic traffic model. This model represents a tool for describing traffic operations at lane closures and estimating the variables of interest. Two major objectives of the study reported here are:

1. To develop a stochastic traffic simulation model to measure the performance of the lane closure system during highway rehabilitation.
2. To validate the model through a variety of field observations in order to ensure that the model is performing close to the real situation.

Once the model is validated, it can be used to determine the optimum location of a traffic control sign which results in minimum traffic delay and safety hazards.

2 DEVELOPMENT OF THE TRAFFIC MODEL

The simulation model is designed to serve as a general purpose application model in the sense that it can be used to analyze a multi-lane unidirectional highway with multi-lane closures. The maximum number of lanes has been fixed at six, and the number of lane closures could be between one and one less than the number of lanes.

The general logic of the model is based on the discrete event simulation principle and the filing utilities of the SLAM II (1986) language have been employed.

Each vehicle is treated as an entity in the model and is kept in a file corresponding to the lane that it is traveling in. The vehicles are ordered in each file based on their distance from the termination point, i.e., the closer they are to this point, the higher their rank is in the file. Arrivals to each lane are scheduled routinely and the vehicle and driver characteristics are assigned upon generation. The following sections explain different components of the model.

2.1 Arrivals

In this module all the characteristics of vehicles and their drivers are assigned according to the specified distributions. These characteristics are saved in a number of attributes. At the entry point, a check is made to ensure that the entering vehicle will not collide with the last vehicle in that lane. Also, if its desired speed is greater than that of the lead vehicle, and its spacing is less than the safe headway, its actual speed is set equal to the speed of the lead vehicle. These assignments are made according to safe headways discussed by Rouphail (1981).

2.2 Updating

The updating procedure in this model is quite different from any other approach introduced in the literature. Other models use a fixed length time interval to update the status of the system. As a result, if a significant event takes place between two updating times, the effect could be too serious to allow the system to wait for the next updating time.

In this model the principle of next event modeling was followed. In this modeling philosophy the appropriate action is taken only if there is a significant effect. That is, the system is updated only if necessary. The need for such updating is triggered by a significant event. The occurrence of such an event is independent of the time elapsed from the last event. This event could be the need for a vehicle to decelerate or initiate a merging maneuver. Therefore, if one element of the system needs an updating, the entire system will be updated as a result.

The acceleration of each vehicle is updated based on the general nonlinear car following equation introduced by Gazis et al (1961). The speed and position of each vehicle, respectively, are updated using the relations given by Gerlough and Huber (1975).

At the end of each updating, a check is made to see whether there is a vehicle that has to merge. This merge is initiated after the vehicle is within the legibility distance of a control sign. If a gap of acceptable size in the adjacent lane is available and all the conditions are satisfied for a safe merge, then lane changing procedure is initiated.

2.3 Lane Changing

The merging maneuver depends on many factors. A proper merge consists of observation, gap selection and gap pacing, and the characteristics of the mainstream traffic. In the observation phase, the driver must establish a plan to take the vehicle into a gap in traffic without disrupting that traffic. Gap selection and gap pacing require realistic estimates of time, speed and distance in terms of the vehicle's capabilities and other conditions. The characteristics of the mainstream traffic deals with the way they respond to the merging vehicle. In principle, Lane changing is divided into two categories, free and forced merge.

Free merges often take place when the drivers are following a slow traffic and have enough gap in the adjacent lane(s) to pass that traffic. In such cases, usually the gap sizes are larger for a safer and more comfortable lane changing maneuver. This logic has been implemented in the model for the situations where the vehicle is in one of the open lanes or is in the closed lane but before the sign. Therefore, in such occasions if the vehicle is following a slower vehicle, it attempts to change its lane. This process consists of looking for a gap of appropriate size in the adjacent lane(s) and starting the merge into the lane with the larger gap. The free merge process is completed as soon as the vehicle is in the target lane.

Forced merges often take place when the vehicle has to change its lane due to some reason other than the slower traffic in front. For instance, for the vehicles in the closed lane or on an entrance ramp or the vehicles in the open lanes which have to exit from a ramp. For such vehicles an attempt is made at every updating time until a safe gap is found for them to change the lane. However, for the traffic in the closed lane, more activities are involved.

The lane changing maneuver is initiated after a few conditions are checked. For instance, a check is made to see whether or not they are within the legibility distance of the next sign. The rule of thumb on required distance is 50 ft/in of character size. Studies by Rockwell et al (1981) have shown that this distance depends on letter size, vehicle speed, driver visual acuity and location of driver with respect to the sign. Their suggested values for the maximum legibility distance are higher than those from the rule of thumb. That is because of the assumption that all drivers have 20/20 vision. In this study this distance, for each driver, is assigned as 100 ft.

2.4 Model Output Analysis

At the end of the simulation run, all the statistics regarding the volume in and out, gap sizes at the time of merge, and the performance measures such as delays, percentage of unsafe decelerations, etc. are printed. In addition, the results of data collection on the highway are presented in the form of descriptive statistics and histograms. These results are then compared with those obtained from the field observations to see if they closely agree to one another. Furthermore, confidence intervals on the responses of interest are estimated using the Batch Means Method (1978).

2.5 Inducing Accidents

In general, the model is designed in such a way that in the absence of a disturbance, there will not be any accidents. That is, it is assumed that if everyone drives the way they should and all vehicles respond as desired, no collision will take place. Nevertheless, the model has the capability of generating such events if a disturbance is induced into it. This disturbance could be induced to the model by means of sudden lane changing maneuvers or drop in speed. Furthermore, attempts have been made to make the model as flexible and general as possible so that a wide variety of situations can be studied and analyzed.

3 VALIDATION OF THE TRAFFIC MODEL

In order for the model to reflect the actual traffic patterns on highways, it had to be validated. The data collected for this study were in the form of video tapes containing observations of traffic both with and without lane closures. The model was first validated with a highway segment without lane closure to make sure that it could perform as expected and produce sound results that complied with theoretical concepts as well as the field observations. These results showed close agreement. To check the distributions, the histograms of speeds and headways were plotted. The model was validated in two steps.

3.1 Theoretical Validation

It is known in the traffic flow theory that the volume is a product of speed and density. To test whether the model shows that such relation exists, several traffic volumes were tested and the results of the average speed and density were gathered for each volume. The results of this experiment are summarized in Table 1.

Table 1: Comparison of the results obtained from Model with those of the Macroscopic Analysis

Volume vphpl	Density vpmpl [1]	Speed mph	Density * Speed vphpl [2]
1953	62	31.5	1953
1840	48	38.3	1838
1660	31	53.5	1659
1500	28	54.5	1526
1476	27	54.5	1472
1328	24	54.6	1310
1156	21	55.5	1166
1080	19	56.3	1070

[1] vpmpl: vehicles per mile per lane
[2] vphpl: vehicles per hour per lane

To make sure that these results are obtained independently from one another, the speed was calculated by dividing the average time that each vehicle spent in the system by the length of the highway. The density was determined by taking the average of the number of vehicles that were in the system at any given time. The volume was the number of the vehicles leaving the system extrapolated for one hour period. These parameters were also compared with the standards set in the Highway Capacity Manual (1985). Figure 1 shows the result of this comparison.

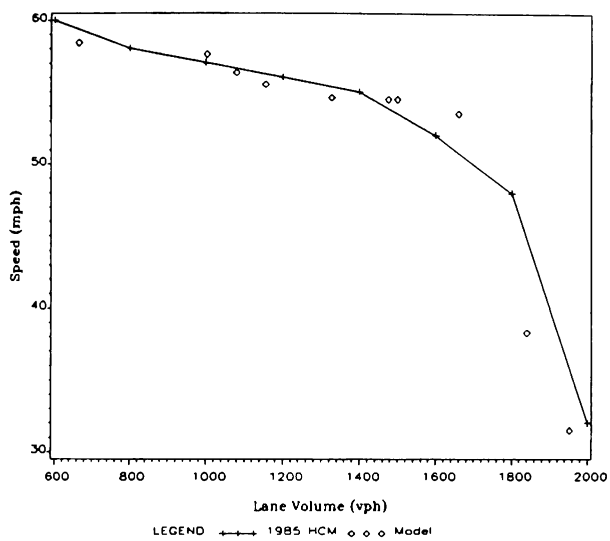

Figure 1. Speed-Volume Relationship Based on the Model and HCM Standards

3.2 Field Validation

An extensive effort was made to validate the simulation model. Video camera was the means of data collection. Eisenhower, Edens, and I-88 expressways in Chicago area were the primary targets of data collection. To get a feeling of traffic variation at different locations along the highway, the data collection stations were located at two different points, one about a mile upstream from the lane closure and the second one around the construction zone. Headways and speed distributions were the primary variables of interest. To double check the results obtained from the video tapes for accuracy, a radar gun was also used for speed estimation. The data were collected at different times to get a good cross section of the traffic flow. The information gathered in one station was used as a means of model calibration and the information at the other station was used for validation. The model was able to generate the same speed and headway distributions at the first data collection station. Several different distributions were examined for the best fit to speed and headway data. The log-normal distribution provided the best fit for arrivals into the model. Likewise, several distributions were tested for speed assignments. Among all of them, the normal distribution proved to provide the best fit. This is in line with the fact that in the field of transportation, the normal distribution is almost always used to explain speed data. To compare the values of the field observations for speed and headway, with those generated by the model, a student t test was used. In all these cases, the difference between the two population means was statistically insignificant.

Comparing the results of the field studies with those obtained from the model at the second data collection point proved to be more complicated than the first station. The manipulation of the car following parameters was the key in validating the model. In order to match the results of the model with those of the field observations, numerous simulation runs were made. In each run a parameter of the car following model was changed to see the effects on the overall results. The effort was focused on coming up with one set of parameters that applied to all cases. After trying many different combinations, an appropriate set of values for parameters were determined. The results presented here are based on these values.

The data were reduced by using a monitor and a video cassette player with frame by frame feature. Two points were marked on the TV screen whose distance was already measured at the site. For every lane, the time that each vehicle passed the first marked point was recorded. Headways were calculated by the difference between the time that two successive vehicles passed that point. To determine the speed, the time that each vehicle passed the second marked point was also recorded. An estimate of the speed was obtained by dividing the time difference that took the vehicle to pass the two points by their distance.

The data from one of the expressways were used to test the model's response for the case of no lane closure. The results of the model and those of the field studies are shown in Table 2. The values in parentheses in Table 2 are means and standard deviations of speed.

Table 2: Speed and Volume Statistics from Model and Eisenhower Expressway with No Lane Closure

Information	Lane	Station 1 (Entry pt.)		Station 2 2000 (ft)	
		Field	Model	Field	Model
Speed (mph)	1	(58,3)	(59,2)	(58,3)	(60,2)
	2	(56,2)	(57,2)	(56,2)	(57,2)
	3	(55,3)	(55,3)	(54,3)	(55,3)
	4	(52,4)	(52,4)	(51,4)	(52,4)
Volume (vph)	1	1368	1404	1452	1380
	2	1392	1332	1440	1356
	3	1512	1620	1476	1632
	4	1236	1236	1128	1284
Percent	1	25.0	25.1	26.0	24.4
	2	25.0	23.8	26.0	24.0
	3	27.0	28.9	27.0	28.9
	4	23.0	22.2	21.0	22.7

For the case of a lane closure, field observations were collected for several volumes. A sample of these observations along with those of the model for a volume of 4600 vph is shown in Table 3.

Table 3: Results of Field Studies and Model for a Volume of 4600 vph at Two Data Collection Stations on Edens Expressway

Information	Lane	Station 1 (Entry pt.)		Station 2 6200 (ft)	
		Field	Model	Field	Model
Speed (mph)	1	(59,4)	(57,3)	(25,7)	(25,9)
	2	(59,4)	(56,3)	(23,6)	(25,8)
	3	(59,4)	(58,3)	(39,8)	(30,11)
Volume (vph)	1	1860	1848	1728	1596
	2	1764	1764	1464	1668
	3	984	984	408	456
Percent	1	40.4	40.2	48.0	43.0
	2	38.3	38.4	41.0	44.8
	3	21.3	21.4	11.0	12.2

Considering the stochastic nature of the model, the results indicate a high degree of validity for the model.

4 EXPERIMENTATION WITH THE MODEL

Once the model was validated, it was used to study a number of significant factors which affect highway traffic. These factors are construction lane closure, warning signs, speed limit signs, and accidents. Each factor was studied through a set of experiments. The detailed results of these experiments will be reported in a separate article. Following is just one example of these results.

A three-lane highway was selected to do the experimentation as the model was validated using such highways. Other advantages of a three-lane highway are that they show the impact of the closed lane as well as the interaction between the two open lanes, and at the same time, they are efficient computationally and use less computer resources.

The model was used to see how altering the location of a control device could have an impact on the traffic delay. If the sign is located far from the lane closure, the closed lane would not be used as efficiently which results in a reduction in the highway capacity. On the other hand, if the sign is too close to the taper, it creates a dangerous situation when the drivers try to make a forced merge into an open lane. So, there is a trade off between the two scenarios. Addressing this trade off was one of the objectives of this research.

Each experiment consisted of six runs. The first run was without a lane closure to get an estimate of the time it would take for the traffic to travel through free of any disturbance. The successive runs were executed with lane closure with the location of the sign moved closer to the taper in each run. The sign locations were altered from 3500 to 500 ft with decrements of 1000 ft. In practice, the first merge sign is installed about half a mile (2640 ft) from the beginning of the construction taper.

Each simulation run had a five-minute warm up period in order to reach the steady state and another 20 minutes during which the vehicles were flagged so that their time in the system could be recorded for delay calculations. The run was completed as soon as all the flagged vehicles left the system. The delay for each run was calculated by subtracting the average time in the system without lane closure from that of with closure.

A variety of traffic flow rates, from low to high, were tested by the model to determine where the control signs had the most impact on the average delay. Since the capacity of each highway lane is around 2000 vph, a range of volumes from 1000 vehicles per hour per lane (vphpl) to the capacity were examined. A sample of these experiments is discussed below.

The traffic volumes considered for this case varied from 3000 to 5500 vph. The experiments were divided into two ranges of volumes, low and high. Low volume range was defined as 3000-3800 vph which is below the capacity of the two open lanes. High volume range was 3900-5500 vph.

The results of the average traffic delay for volumes 3000 to 3800 are depicted in Figure 2. It should be noted that the volumes on the graph are the overall volume into the system. The capacity of the highway is determined by the capacity of the number of open lanes, that is between 3600 to 4000 vph in this case.

Looking at Figure 2 one can observe that for volumes of up to 3500 vph, the location of the sign has no impact on traffic. Above 3500 and up to 3800 vph, there exists a pattern. This pattern indicates that for volumes 3500 vph and below, the sign should be far from the taper because of minimum delay. For volumes 3600 to 3700 vph the best location of the sign seems to be between 1500 to 2500 ft from the taper. Graph of volume 3800 vph, however, show again that the location of the sign has only a moderate impact on traffic delay. This volume is close to the capacity of the two open lanes and can be considered as a point of transition between medium and high traffic flows. All delay curves in Figure 2 suggest that the sign location should not be any closer to taper than 1500 ft.

The results of the traffic delay for high traffic volumes are shown in Figure 3.

For all the cases in this figure the system is saturated and the volumes are over the highway capacity. This plot does not show a clear pattern and indicates that there is no significant impact on traffic due to the location of the sign.

To summarize the results of this experiment, one can conclude that for low traffic volumes of up to 3500 vph, the location of the sign does not have a significant impact on the traffic delay. However, locating it far from the taper results in slightly lower delays. For volumes 3600 and higher up to the highway capacity, the sign has some influence on the delay and safety and its best location is between 1500 to 2500 ft from the taper. For volumes over the capacity again, the sign does not play a significant role, but locating it closer to the construction taper would show a slight improvement. These findings are in line with the earlier discussion in this section regarding the efficient use of open and closed lanes.

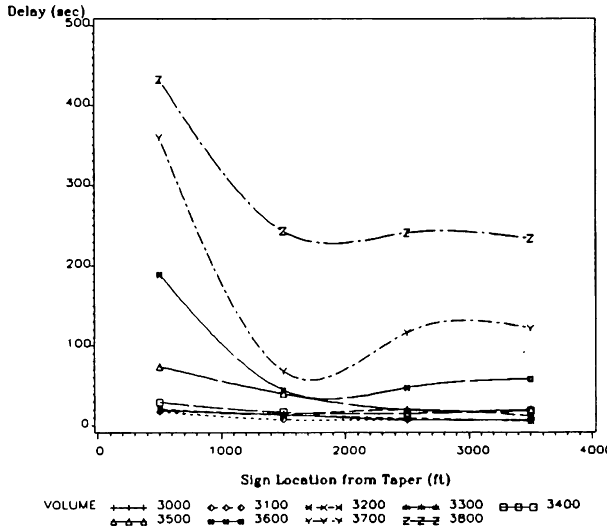

Figure 2. Average Traffic Delay for Volumes 3000-3800 vph, Three-Lane Highway with Right Lane Closed

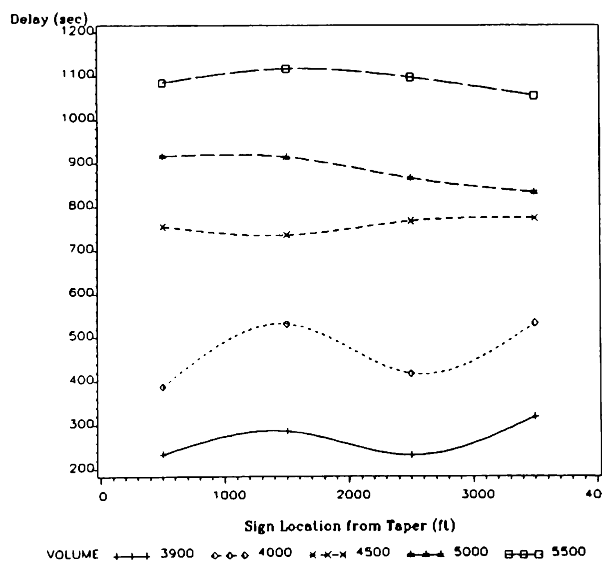

Figure 3. Average Traffic Delay for Volumes 3900-5500 vph, Three-Lane Highway with Right Lane Closed

5 SUMMARY AND CONCLUSIONS

The problem of traffic delay and safety on highways around work zones was discussed. It was suggested that the traffic control procedures at these sites be analyzed by utilizing a traffic simulation model. Since introducing any new procedure at the highway work zones may result in hazardous situations to the motorists, a simulation model can serve the purpose quite well. By means of such a model, one can experiment different procedures and study the results of interest without actually interrupting the traffic or endangering the drivers' lives.

The simulation model was validated using the field data on several highways with different volumes and configurations. After the model was tested and validated and proved to reflect the actual traffic patterns observed on highways, it was used as a tool to perform a variety of experiments. These experiments were focused on the events that are observed on highways quite frequently such as: lane closures and effects of control signs on the traffic delay, the effects of weather conditions on the traffic, the effects of speed limit signs, and the effects of accidents on the same or the opposite bounds.

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