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Abridgment

FREESIM: A Microscopic Simulation Model of Freeway Lane Closures

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Development of a model to simulate traffic operations at freeway lane closures is described. The model logic is based on a rational description of the behavior of the drivers in a freeway lane-closure situation. The simulation program is written in SIMSCRIPT II.5 programming language. An application of the model is given with evaluation of potential safety impacts of reduced speed zones in freeway lane closures at different levels of assumed driver compliance.

With the Interstate system nearly complete, the emphasis has now shifted toward continued maintenance of this freeway network. Resurfacing, upgrading, and other corrective measures are required to maintain the original design standards and to eliminate previously unrecognized safety hazards. Construction and maintenance work activities requiring temporary closure of a freeway lane represent a frequently encountered and potentially hazardous situation. A study of road-under-repair accidents in Virginia found, for example, that of 426 accidents (for which the information on traffic control characteristics was available), 47.9 percent occurred at lane closures *(1)*.

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Freeway lane closures require properly developed traffic control plans to minimize the disturbance to the traffic flow and provide for the safety of both drivers and the working crew. Drivers approaching a work zone in the closed lane must receive and understand the information that they need to change lanes and merge into the traffic in the open lane. Although this in itself does not appear to be an unusually demanding driving task, problems still appear to develop, resulting in rear-end collisions, sideswipes, and single-vehicle fixed-object accidents *(2)*.

Improving traffic control systems requires comprehensive information on the relationship between control strategies and the quality of traffic flow (e.g., delay, travel time). Computer simulation provides an excellent basis for evaluating a wide sprectrum of traffic management schemes within the framework of controlled experiments. In this paper, development, verification, validation, and application of a microscopic simulation model (FREESIM) of traffic operations at freeway lane closures is described.

FREESIM SIMULATION MODEL

FREESIM is a microscopic, stochastic simulation model; vehicles are represented individually and their detailed, time-varying behavior is simulated. The model logic is based on a rational description of the behavior of the drivers in a lane-closure situation.

Vehicles are generated randomly from a shifted negative exponential distribution of arrival time headways, and are advanced in the system using a classical car-following approach; that is, each vehicle attempts to advance at its desired speed while maintaining a safe following distance from the vehicle ahead.

The lane change from the closed lane is described by a stimulus-response approach *(3)*. The basic behavioral assumption of the stimulus-response approach is that each traffic control device (or the view of the lane closure itself) can be considered as a stimulus and each will induce a different proportion of drivers to change lanes.

The vehicles are processed through the conventional gap-acceptance procedure to determine whether the lane change is possible.

The stimulus-response probability distribution was calibrated based on a survey of 229 drivers conducted at several freeway lane-closure sites *(4)*. The information processing time and the response initiation time for traffic control devices used in freeway lane closures were calibrated by using data from McGee et al. *(5)*.

The representation of the traffic control devices in the simulation program includes the advance warning signs recommended in the Manual on Uniform Traffic Control Devices (MUTCD) and a flashing arrow board for single-lane closure in multilane freeways *(6)*. FREESIM, as an option, can simulate the effect of a reduced-speed zoning by specifying the parameters (i.e., legibility, information processing time, and response initiation time) for a speed-limit sign and the assumed proportion of the drivers complying with it.

FREESIM can simulate single-lane closure of a freeway section with two or three unidirectional lanes of any reasonable length. For each lane, up to five data collection points can be simulated at user-specific locations to collect data on the ongoing behavior of the vehicles in the system, namely, speed and headway distributions. An additional data collection point is provided (by default) at 500 ft upstream of the system exit point.

SIMULATION INPUT

The input data (all free format) required for a simulation run include four types:

1. Simulation run parameters: simulation time, warm-up time, time interval between vehicle trajectories data collection, time interval between status listings, and random number seeds;
2. Roadway parameters: length of freeway section, location of the taper and of the headway, and spot speed data collection points;
3. Traffic parameters: approach volume, proportion of trucks, mean speed factors, and standard deviation of mean speed;
4. Traffic control device parameters: preference, legibility distance, type and speed limit; and
5. Vehicle and driver characteristics: length and maximum emergency deceleration rate of various vehicle types and mean brake reaction time of the drivers.

OUTPUT DESCRIPTION

The standard output of the program includes a title page and a list of all relevant input parameters. The simulation results are printed in the following general classification:

1. Simulated data collection points information: distributions and summary statistics of spot speeds and time headways at user-specified locations;
2. Summary statistics on measures of performance: travel time, delay, and speed gradient;
3. Volume-throughput data: throughput, input, and output volumes;
4. Lane-changing data: frequency distribution and statistics of lane-change initiation points and gap acceptance; and
5. Deceleration: number of uncomfortable and emergency decelerations.

PROGRAM DESCRIPTION

FREESIM was developed using SIMSCRIPT II.5 programming language, developed by CACI *(7)*. SIMSCRIPT II.5 is a powerful simulation programming language, both for discrete-event and continuous simulation. The SIMSCRIPT programs are composed of free-form, English-like statements; hence, the SIMSCRIPT II.5 source program becomes a useful part of the model documentation.

FREESIM is implemented on an AMDAHL 470/V8 system, which is an IBM-compatible computer. For a 6,000-ft freeway section, the average ratio of real time to central-processing-unit time varied from 70:1 to 40:1 as the two-lane approach volume varied from 1,200 to 1,800 vehicles per hour.

VERIFICATION AND VALIDATION

Verification of the simulation program was performed by operational testing of the car-following and lane-changing algorithms and sensitivity analysis of measures of effectiveness to the exogeneous (input) variables.

In the operational testing of the car-following algorithm, velocity responses of the vehicles to artificially induced speed disturbances and a blockage were observed. The tests indicated that the car-following algorithm shows all the desired characteristics: realism, stability, and reasonable oscillatory following behavior.

In the operational testing of the lane-changing component, the lane-changing behavior was observed for a range of values of traffic volumes in the closed lane of a two-lane freeway section. This testing emphasized the

- Compatibility of the lane-changing algorithm with the car-following algorithm, and

• Performance of the lane-changing algorithm at high levels of traffic volume.

Sensitivity analysis indicated that the measures of effectiveness (e.g., mean speeds and time headways at various locations in the simulated freeway section, merging proportions) were sensitive to the changes in input parameters for the lane mean speeds and stimulus-response probability distribution. The changes (up to 20 percent) in other input variables (e.g., information processing time, proportion of trucks, mean brake reaction time, and maximum emergency deceleration rate) did not have any appreciable effect on the simulation output. The implication of this analysis is that a strong data base is necessary for the calibration of the lane mean speeds and the stimulus-response probability distribution.

The simulation program was validated by comparing simulated time headway, speed, and merging distributions with four sets of actual observations obtained from three different rural freeway lane-closure sites *(4)*.

Compared with data from the field studies, the simulation model reproduced headway and merging distance distributions accurately. The comparison of simulated versus observed speed distributions indicated reasonably good agreement.

Also, the simulation model outputs representing the macroscopic traffic flow parameters (i.e., speed, flow, and throughput) and lane-changing frequencies were compared with some well-known empirical data from the literature. The simulation output compared well with the data from the revised Highway Capacity Manual *(8)* and Greenshield's Model *(9)*. Similarly, the simulated lane-changing frequencies were compatible with the data from the Northwestern University lane-changing study and INTRAS simulated observations *(10)*.

MODEL APPLICATION

A practical application of the model is given with simulation experiments to evaluate potential safety impacts of reduced speed zones at freeway lane closures at different assumed levels of compliance. The introduction of reduced speed zones in freeway lane closures is a controversial and not well understood aspect of traffic control *(11)*. Although reduced speed implies greater safety, at least intuitively, it introduces a disturbance in the traffic flow that may have negative impact—that is, increased probability of shock-wave formation upstream of the construction zone. The problem can be critical at high approach volumes.

A fractional factorial design was developed for the analysis of three independent variables: speed limit, compliance with the speed limit, and two-lane approach volume. Compliance levels of 0.33, 0.66, and 1.00 were used for each of the two reduced speed limits implemented: 50 mph and 45 mph. Four levels of two-lane approach volumes (vehicles per hour) were used: 800, 1,200, 1,500, and 1,800.

Three safety-related measures of performance from FREESIM output were selected as the dependent variables: number of uncomfortable decelerations per hour, variance of speed, and proportion of headways less than 2 sec in open lane at beginning of transition zone. An uncomfortable deceleration is defined as one that exceeds by more than 2 ft/sec/sec the deceleration rate normally considered comfortable at a given speed. The variance of speed at the transition zone is generally considered as the proxy variable for potential rear-end accidents upstream. Similarly, the presence of short headways in a transition zone can be considered as increasing the likelihood of rear-end collisions in the approach area.

SIMULATION RESULTS

The results of simulation experiments for the approach volume level of 1,800 vehicles per hour are given in Table 1. The results presented in the table are based on the average of five replications. The simulation results for all volume levels are described in detail elsewhere *(12)*. These results are presented here for the sole purpose of demonstrating the application of the model.

TABLE 1 SIMULATION RESULTS

Speed Limit (mph)	Compliance Level	N^a	V^b	P^c
55		1,258.0	102.1	69.8
	0.33	1,218.0	97.1	68.2
50	0.66	1,218.0	107.5	67.2
	1.00	1,514.8	112.4	67.5
	0.33	981.6	83.1	67.9
45	0.66	1,178.0	81.6	68.0
	1.00	1,052.0	84.7	67.8

^aN = uncomfortable deceleration/hr.
^bV = variance of speed (mph²).
^cP = proportion of headways less than 2 sec.

The introduction of the 45-mph speed zone reduced the number of incidents of uncomfortable decelerations at all levels of compliance. However, the 50-mph speed zone was ineffective. In summary, it required a 10-mph reduction in the desired speed of the simulated group of complying drivers to produce the desired impact on the traffic flow.

The results were similar with regard to the speed variance measured at the beginning of the taper. The impact on headway distribution, measured by the proportion of headways less than 2 sec, was small but consistent in all cases.

The impact of the introduction of speed zones at lane closures depends heavily on approach volumes. The data presented in Table 1 represent high-volume conditions. By generating speed data at the beginning of the taper area, it was possible to demonstrate that approach speeds were constrained by near-capacity conditions; consequently, the introduction of speed zones had little potential to improve conditions. The benefits were considerably different at lower volumes.

OTHER POTENTIAL APPLICATIONS

FREESIM can be used for a variety of practical applications, in particular, evaluation of traffic performance in freeway lane closures under different control schemes.

In the MUTCD *(6)* the recommended traffic control treatment for typical freeway lane closures is described. However, accident experience at lane-closure locations indicates that the minimum standards applicable for typical situations may not be adequate for all situations. FREESIM can be conveniently used to evaluate the impact of alternative advance warning signs or novel experimental signs on traffic performance in freeway lane closures. A before-and-after study could be conducted to evaluate the changes in traffic performance resulting from different control schemes. In the same format, FREESIM can also be used to evaluate the effect of nonconformity to the MUTCD standards such as sign misplacement or omission, poor maintenance, and use of confusing message. In these applications, the recalibration of the stimulus-response probability distribution would be required, particularly because the output variables were found to be sensitive to changes in this distribution.

An interesting application of the simulation model would be to assess the influence of problem drivers—for example, inattentive drivers or risk takers—on the behavior of the system. The influence of target driver groups such as speeders and risk takers can be included by appropriately modifying the simulation input parameters of drivers' performance characteristics, for example, speed distribution and distribution of brake reaction time.

The simulation program can also be used in optimization applications, such as the determination of optimum length of a single-lane zone for different approach volumes.

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