Lane Closures at Freeway Work Zones: Simulation Study

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A study of freeway lane closures at work zones is described. It involved the development of a microscopic computer-simulation model. Vehicles in platoons are controlled by a car-following rule. The merging behavior is controlled by the information provided by the traffic-control devices, by personal preference for early or delayed merge, and by the availability of gaps in the open lane. The prescription of personal preference was based on a driver survey. The model also checks for the possible obscuring of signs by large vehicles. Field tests produced varied results, but average speeds and throughput (vehicle miles per hour squared) generated by the model fit between the classical Greenshield's model and those calculated by the 1980 revision of the Highway Capacity Manual. A factorial simulation study was conducted to investigate traffic behavior under a variety of conditions, represented by different volume levels, traffic compositions, merging preferences, speed control and compliance, and advance-warning distances. Delay and standard deviation of speed at the taper were generated for each factor-level combination. The results generally confirmed what was expected. Noteworthy is the indication that full compliance with a reduced speed limit of 45 mph would increase delayed merges within the taper area in the volume range simulated.

The problems associated with the safe and efficient conduct of traffic at work zones have received considerable attention in recent years. The Federal Highway Administration (FHWA) initiated a coordinated research program in 1975: Project 1Y--Traffic Management of Construction and Maintenance Zones. The purpose was to generate the basis for the development of new concepts, methods, and approaches to traffic management in construction, maintenance, and utility work zones. It resulted in the undertaking of numerous studies with wide scope and ranges of objectives.

Work activities that require lane closures and force traffic to merge into the open lane(s) represent a frequently encountered and a 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). The same study found that close to 80.0 percent of the work-zone accidents can be attributed to driver error. 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 open-lane traffic. Although this in itself does not appear to be an unusually demanding driving task, problems seem to develop that result in rear-end collisions, sideswipes, and single-vehicle/fixed-object accidents (2).

The objective of the research project described here was to study the operation of lane closures at construction sites on rural freeways. Two issues were addressed in particular:

1. Merging patterns from the closed lane into the open-lane traffic and
2. Speed reduction at work zones.

The approach taken by the study team was to build a simulation model supported by field studies and driver surveys.

CHARACTERISTICS OF SIMULATION MODEL

The microscopic digital simulation model Freeway Construction (FREECON) of lane closures at freeway construction sites is written in FORTRAN IV language and it uses the GASP IV simulation package of Pritsker (3). The model is based on the realistic description of the movement of a vehicle approaching a lane-closure site. The two major rules applied in previous freeway simulation models are the car-following and gap-acceptance rules. In this model, several additional features were needed relevant to traffic control at lane closures.

Driver Reaction to Merging Stimuli

Signs, arrowboards, and finally the delineation of the taper itself provide the information or stimulus to merge from the closed lane into the open lane. A driver survey was conducted to identify what proportion of drivers reacts to each stimulus. Each unit of driver and vehicle is randomly assigned by the model into one of the groups in an attempt to represent realistic merging behavior (i.e., a certain proportion of the drivers will begin searching for an acceptable gap at the first sign, whereas others might wait until the taper or the construction site becomes visible).

Driver Reaction to Speed Control

As an option, the model can also specify drivers' reaction to speed control (e.g., comply with advisory speed limit sign).

Traffic-Control Device (TCD) Design Constraint

The location can be specified for each TCD within the simulated freeway segment, and a recognition distance is also assigned to represent a particular design (e.g., size).

TCD Visibility Constraint

In many instances, a driver is unable to see a sign because his or her line of sight is blocked by another vehicle. In the model, vehicles are represented by their physical dimensions, and one of the subroutines checks for potential blockage of TCDs by large vehicles.

TCD Information Acquisition Constraint

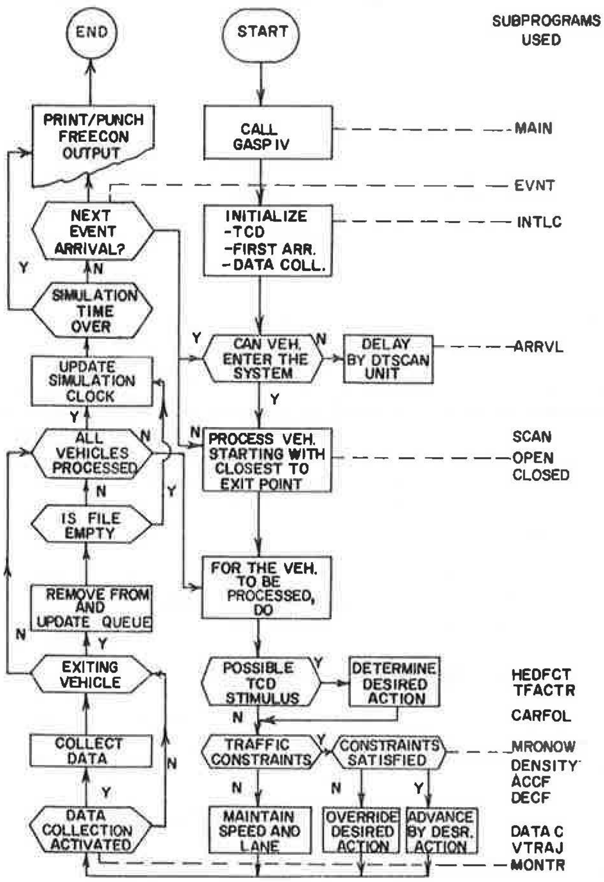
Each TCD is assigned a minimum required information-processing time. In free-flow traffic, drivers should have ample time to look at signs long enough to understand the message. In high-density flow, however, more time is spent on fixating on other vehicles and less is available for sign recognition (4). An algorithm has been developed that relates the maximum duration of fixation on the various TCDs to the time headway between two vehicles in the car-following mode.

MODEL STRUCTURE

FREECON consists of a main program and 18 supporting subprograms and functions. The model is microscopic in nature; that is, each driver-vehicle unit is identified as a separate entity. Periodic updating of each vehicle's status is performed at 1-s intervals.

Figure 1 illustrates the general simulation logic as it applies to the microscopic driver-vehicle entities in the system. Also shown are the subprograms related to each step in the model.

Figure 1. Flowchart representation of model logic.



Eight basic and interacting components constitute the core of the model.

Driver-Vehicle Component

On entering the work zone, each individual driver or entity is assigned a set of 20 attributes, some of which are periodically updated during a simulation run. In this version of the model, all attributes were assigned independently. This was later revised to account for driver groups exhibiting 16 similar attributes such as speed and gap acceptance. A brief description of each attribute follows:

DENTR: time of entry (or entries), randomly assigned from a distribution of time headways in the corresponding lane or lanes.

DDSPD: desired speed (ft/s), randomly assigned from the distribution of vehicle speeds upstream of the work zone.

DLANE: lane of travel (1 = open lane, 2 = closed lane), randomly assigned based on the distribution of traffic among the approach lanes.

DSPL, DSPN: vehicle speed at end of last and current updating intervals, respectively (ft/s).

VTYPE: vehicle type (1 = passenger car, 2 = truck), randomly assigned based on the traffic composition upstream of the work zone.

DPSOL, DPSON: vehicle position at end of last and current updating intervals (ft); DPSON is the ranking attribute in the driver-vehicle file with a high-value-first (HVF) queue discipline.

TMRGS, SPST: selected merge and speed simulation codes, respectively. [Each driver entering the work zone is assigned a set of merge and speed stimuli. This assignment is based on the survey of 229 drivers conducted at several freeway construction lane-closure sites. Among the results were the following: 45.4 percent of drivers merge at the earliest opportunity, 13.1 percent of drivers merge after having passed a few cars, 9.3 percent of drivers merge after having seen other drivers merge, 20.5 percent of drivers merge after having seen construction activity, and 11.7 percent gave no answer. From these results, as a first approach, a representative probabilistic distribution function of drivers' response to merge stimuli was formulated. More work is being done now on this aspect of the model. Similar treatment is applied in the development of a typical speed strategy.]

SFIXM, SFIXS: cumulative time fixations on a merge and a speed stimulus, respectively; merges and speed changes in the model are initiated as soon as either value exceeds the minimum information-processing time on the corresponding stimuli.

SLCH: cumulative time spent in the lane-change maneuver(s); the model assumes a 4-s lag between initiation and completion of a lane change.

MCODE: merging attempt code (1 = attempting, 0 = not attempting); introduced to ensure that once a lane-change attempt has aborted, consecutive attempts will be made until a successful maneuver has been completed.

VINDX: vehicle index register; used to trace vehicles' paths throughout the work zone.

TVLST: last time the vehicle's position was updated; introduced to prevent multiple processing of the same vehicle in the same interval.

SPEDG: cumulative speed gradient component; traces speed fluctuations throughout the work zone; final values for each vehicle are determined at the point of exit.

CGAP: driver critical gap (ft); randomly assigned from a gap-acceptance function derived in a related study (5).

DHEAD: desired headway(s); introduced to test whether a speed-control strategy based on reducing headway variance, instead of average speed, could improve the quality of traffic flow; DHEAD may be totally bypassed in the model logic.

TREACT: driver's brake reaction time; randomly assigned from a distribution of brake reaction times developed by Johannsson and Rumar (6).

TCD Component

Ten attributes describing each TCD are introduced in the initialization phase of the model. These are as follows:

SCODE: TCD code, unique to each device (e.g., arrowboard, signs, cones); SCODE is matched with TMRGS, SPST codes in the driver-vehicle component.

SL: TCD placement code; a code of 1 is given for TCD placed on the open-lane side of the road, 2 for those placed on the closed-lane side, 12 for both sides.

PS: location of TCD, measured from vehicle entry point along the longitudinal axis of the road (ft).

WS: lateral TCD placement, measured outward from lane edge (ft).

SLD: recognition distance, as measured in the field (ft).

SLP: upstream recognition point (= SL - SLD).

SDR: minimum information-processing time; SDR is compared with SFIXM or SFIXS in the driver-vehicle component in order to schedule lane and/or speed-change attempts.

SH: message height, measured from pavement level (ft).

ST: type of stimulus; TCDs are categorized as either merge or speed stimuli (example: reduced-speed-limit sign).

SSPD: posted speed limit if different from freeway speed limit (ft/s).

Roadway and Data-Collection System Component

The location of data-collection points can be varied by the user; up to 20 data-collection points may be simulated, 10 for each approach lane. Vehicles crossing any of the simulated detectors activate the corresponding speed and headway registers. Although there is no physical limitation on the simulated length of the zone, the model logic makes it necessary that the termination point be in the single-lane zone of traffic.

In its present form, the model assumes a straight, level road alignment. However, horizontal and vertical curvature effects on TCD recognition distance can be readily manipulated in the TCD component.

Vehicle-Generation Component

Vehicle arrivals into the work zone are scheduled from a probability function of time headways. Nine such functions are available in the model, each of which is given a unique code provided by the user as input (7). Desired speeds are generated in the same fashion. Tests are internally conducted in the model to ensure that the car-following rules are satisfied at the entry point. Modeling shifted distributions is readily available in the GASP IV input format.

Car-Following Component

The car-following model selected in the study closely follows the noncollision constraints developed in the INTRAS simulation model (8) with some modifications. Three car-following rules are defined, as follows:

$$X_t - Y_t \geq L + CV_t \qquad 0 < V_t \leq U_t \tag{1}$$

$$X_t - Y_t \geq L + CV_t + (V_t^2 - U_t^2)/2E \qquad V_t > U_t > 0 \tag{2}$$

$$X_t - Y_t \geq L \qquad V_t = U_t = 0 \tag{3}$$

where

X_t = position of lead vehicle at time t (ft),
Y_t = position of following vehicle at time t (ft),
U_t = speed of lead vehicle at time t (ft/s),
V_t = speed of following vehicle at time t (ft/s),
L = overall length of lead vehicle (ft),
C = brake-reaction time of following driver, and
E = maximum acceptable deceleration rate (ft/s²).

Since vehicles' positions are updated every second, it follows that the lead-vehicle position and speed are first determined at time t + 1; from Equations 1, 2, or 3, a maximum permissible acceleration rate (a_{max}) is determined. The actual acceleration rate (a) is computed as follows:

$$a = \min(a_d, a_{max}, a_v) \tag{4}$$

where a_d is the desired acceleration rate based on current (V_t) and desired (DDSPD) speeds and a_v is the limiting acceleration rate based on current speed and vehicle type. The following-vehicle speed and position are then updated as follows:

$$V_{t+1} = V_t + a \tag{5}$$

$$X_{t+1} = X_t + V_t + \tfrac{1}{2}a \tag{6}$$

Lane-Switching Component

This component handles all merging maneuvers. When a lane change is attempted, tests are conducted to ensure that the car-following rules in the destination lane are satisfied. Additional tests are made to determine whether safe merging gaps are acceptable to the driver, based on the gap-acceptance function.

Another feature of this component is the automatic initiation of lane-change attempts for vehicles within the stopping-sight distance of the construction taper. It was assumed that only the car-following rules need to be satisfied to perform a successful merge in the region. Empirical evidence for this assumption can be found in Pahl's study of freeway exit ramps (9).

TCD Information Acquisition Components

This component registers and updates the cumulative time fixations a driver makes on a TCD. In order to initiate a speed (lane-change) response, the cumulative time fixations on the speed (merge) stimulus should exceed the minimum information-processing time for the stimulus. Whether this condition is met before the driver passes the TCD location depends on two factors: (a) presence of obstruction to the driver-TCD line of sight and (b) current headway.

The impact of vehicle headway (h) on TCD information acquisition was modeled by using the following functions:

$$DT_h = 0 \qquad h \leq 0.5\text{ s} \tag{7}$$

$$DT_h = (2H - 1)/7 \qquad 0.5 < h < 4\text{ s} \tag{8}$$

$$DT_h = 1 \qquad h \geq 4\text{ s} \tag{9}$$

where DT_h is the fraction of time a driver spends fixating on TCD while traveling at headway h.

Determination of function parameters was based on preliminary results of driver test studies conducted at freeway lane closures (10). Further refinement of the function may be necessary as additional data become available.

The final form of the TCD information acquisition constraint is stated as follows:

$$SFIXM_i\,(t+1) = SFIXM_i\,(t) + B \times DT_h \geq SDR_i \tag{10}$$

where

$SFIXM_i(t + 1)$ = cumulative time fixations on TCD_i after t + 1 s,
$SFIXM_i(t)$ = cumulative time fixations on TCD_i after t s,
B = binary variable that assumes a value of 1 (zero) if legibility rules are (are not) met, and
SDR_i = minimum information-processing time for TCD_i.

Output Component

The simulation model output component produces the following standard output:

1. Listing of user input data;
2. Descriptive statistics and histograms of speeds and time headways at each data-collection point;

3. Descriptive statistics and histograms of five performance measures: vehicle merging points measured from entry point (ft), vehicle delay, exit volume during simulation period, throughput (defined as the product of exit volume and exit speed and cumulative for all vehicles), and speed gradient (a measure of speed fluctuations for vehicles traveling in the work zone); and

4. Listing of vehicle trajectories at any point during simulation run; trajectory data can be routed to a plotting routine that produces a visual representation of the individual vehicles' paths in the approach, transition, and single-lane areas.

MODEL VALIDATION

The model was first tested by comparing outputs with generally accepted models of the speed-volume-density relationship. Average speeds and throughput (vehicle miles per hour squared) were calculated at volumes ranging from 1000 to 2000 passenger cars per hour per lane in the open lane. It was found that outputs fit between the classical Greenshield's model and those calculated by the 1980 revision of the Highway Capacity Manual.

Field studies were conducted at two construction sites (denoted A,B) with the purpose of testing the model logic. Specifically, the following traffic descriptions were targeted for comparison:

1. Means and distributions of vehicle time headways at each data-collection point,
2. Means and distributions of vehicle speeds at each data-collection point, and
3. Distribution of merging distances, defined as vehicle position (in feet) measured from the first construction sign at which a lane change is initiated into the through traffic lane.

Data Collection and Reduction

An instrumented data-acquisition system, developed by the Systems Research Group of the study team under the direction of T.H. Rockwell, was specifically designed for the purpose of collecting the above-mentioned traffic descriptions.

The system consists of eight 10-ft tapeswitches arranged in pairs. The tapeswitches were laid in the open lane of traffic and covered a distance of 1500 ft. Cable connectors were used to transmit vehicle actuations into a video cassette recorder via a 12-channel video box. A unique code for each tapeswitch (zero to seven) was assigned, which was displayed on a TV monitor for the duration of the actuation. Other elements in the system included a continuous five-digit clock and a video camera. Power was supplied to the various components by means of a portable 4-hp/1900-W, gasoline-powered A/C generator.

Supplementing the system was a number of manual observers who collected pertinent traffic data outside the system's 1500-ft range. Finally, a complete inventory of TCD design and performance characteristics was made prior to data collection.

The recorded vehicle arrival times at each tapeswitch were subsequently reduced and fed into a computer program for the determination of mean values and distributions of speeds, headways, and merging distances.

Results at Site A

Site A involved a left lane closure during a bridge-deck rehabilitation project on the southbound lanes of I-71. Statistical tests were conducted on speed and headway distributions for two independent observation periods (10 min each). Student's t-tests on mean values showed no statistically significant differences at α = 5 percent.

Distributions of speed and headways were then tested by means of the Kolmogorov-Smirnov two-sample test. Results indicated no significant differences except for speed distributions at the two downstream (i.e., last) tapeswitch pairs. The simulated speeds were slightly higher there than the observed speeds. The difference was always less than 2 mph.

Also, the statistical tests showed no significant differences in the cumulative distribution functions of merging distances, which suggests that the typical merging strategy indicated by the driver survey appears to be a valid indicator of drivers' preference in lane-closure situations under the conditions present at site A.

Results at Site B

A substantial difference was found between the field and simulated merging patterns at site B. Drivers were observed to merge much later at site B than at site A. The effective warning distance was only slightly shorter at site B and could not possibly account for the large difference. Geometrics were in general quite similar, but at site A the left lane was closed, whereas at site B, the right lane was closed. A closer look at the lane distribution of the volumes led to a plausible explanation for the difference in merging. Looking at the equivalent hourly approach volumes and approach speeds, we have found the following: approach volumes at site A were 330 vehicles per hour (vph) at 61 mph in the merging lane and 714 vph at 53 mph in the open lane; approach volumes at site B were 451 vph at 48 mph in the merging lane and 190 vph at 55 mph in the open lane.

Although traffic is not distributed uniformly over the roadway, it is worthwhile to express the above-described traffic flows in terms of average spacings in feet. While drivers are obviously not very sensitive to hourly volumes, they can observe and be influenced by the spacings of vehicles around them. At site A, average spacing is 978 ft in the closed lane and 390 ft in the open lane. At site B, the average spacing is 562 ft in the closed lane and 1510 ft in the open lane.

The open lane at site B must have looked empty to the drivers in the closed lane and thus there was no incentive to merge early.

The open lane at site A, however, looked fairly well traveled; thus it provided an incentive to merge early to at least some of the drivers; i.e., as expected, drivers use judgment regarding the urgency of lane changes.

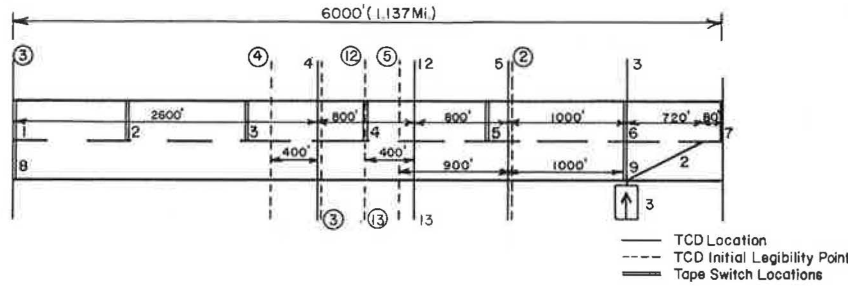
It was concluded, therefore, that the application of the model should be limited to higher approach volumes, perhaps in the range of 1000 vph, combined on the two lanes, provided that the larger proportion of traffic occupies the open lane typical at left-lane closures. Research is under way to develop a merging model more general in scope.

EXPERIMENTS WITH MODEL

Several experiments were conducted with the model with the purpose of testing the sensitivity of some traffic-stream descriptors, merging and speed-control strategies, and TCD performance characteristics on a number of the system's performance measures, by using the site configuration shown in Figure 2.

A complete mixed factorial design was developed for the analysis of five independent variables. These were categorized into traffic-stream factors,

Figure 2. Simulated work zone for simulation study.



TCD	MESSAGE	LOCATION	LEGIBILITY	HEIGHT
2	Taper, Type II Barric.	5200'	1000'	3'
3(I)*	4'x8' Arrow Board	5200'	5200'	8'
(II)	4'x8' Arrow Board	5200'	2600'	8'
4	Right Lane Closed	2600'	400'	7'
5	Symbolic Sign I\	4200'	900'	7'
12(I)	Allow Space for Merging Vehicles	3400'	400'	7'
13(II)	Speed Limit 45MPH	3400'	400'	7'

* I,II, Mutually Exclusive Conditions

driver-behavior factors, and TCD factors:

1. Traffic-stream factors:
   (a) Two-lane approach volume upstream of the work zone at levels of 100, 1250, and 1500 vph
   (b) Proportion of trucks at levels of 0 and 25 percent of approach volume
2. Driver-behavior factors:
   (a) Merging strategy at the following levels: early merging strategy (all drivers in the closed lane attempt to merge at first opportunity), typical merging strategy (as obtained from the driver's survey and validated at site A), and late merging strategy (all drivers in the closed lane attempt to merge only on recognizing the construction activity)
   (b) Speed-control strategy at the following levels: none (no special provisions for speed reduction), 45 mph (all drivers in the open lane comply with a posted 45-mph reduced-speed limit), and special sign [all drivers in platoons (headways ≤ 4 s) increase their headway in compliance with the experimental sign ALLOW SPACE FOR MERGING VEHICLES]
3. TCD factor: Effective warning distance at levels of 1 and 0.5 mile.

Variations in the effective warning distances are modeled by assigning two different legibility distances for the arrowboard.

Dependent variables included mean vehicular delay (DELAY), standard deviation of speeds at the start of lane taper (SSD), and proportion of merges prior to 400 ft from taper (MERG400). The latter variable reflects the relative frequency of occurrence of free versus forced merges. The 400-ft distance was computed as the stopping-sight distance for a vehicle traveling 55 mph and a brake reaction time of 1 s. Thus, all lane changes occurring within the last 400 ft were considered forced merges.

The analysis of variance (ANOVA) technique was used to formulate statistical models for the three performance measures. A level of significance of α = 5 percent was used throughout the analysis.

Interpretation of Results

Results of the ANOVA models are displayed in Figures 3, 4, and 5. All three-factor level interactions were found to be statistically insignificant.

Figure 3. Impact on delay.

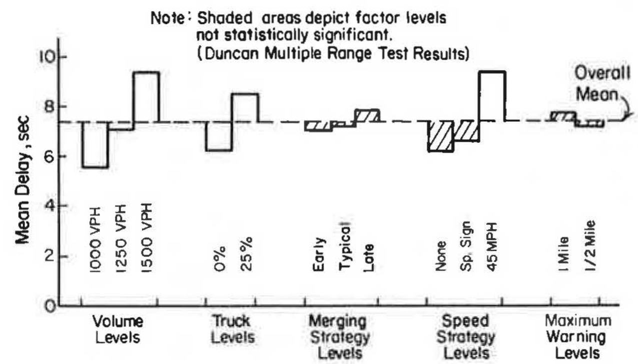
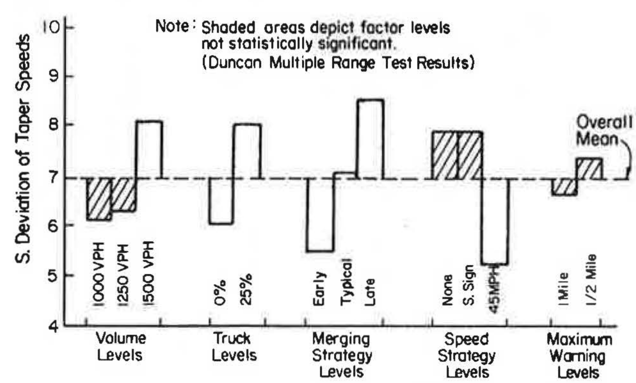
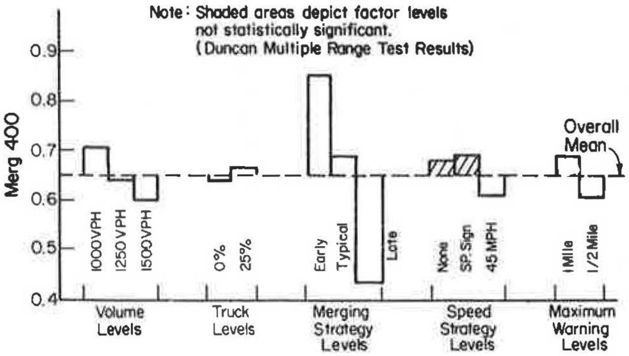


Figure 4. Impact on speed distribution.



Delays (see Figure 3) were found to increase with volume and truck proportion, as expected. The main merging-strategy effect was not statistically significant, although a closer look at the details indicated that delays were highly sensitive to volume levels in the late merging strategy. At the other extreme, delays were all but unaffected by volumes under the early merging strategy. The 45-mph speed limit resulted in a mean delay increase of 50 percent, whereas no statistically significant increase in delays was noted with the experimental sign. The predicted increase in delay is obvious, since delay

Figure 5. Impact on forced merges.



is defined as the difference between travel time at approach speed and travel time at actual speed (in this case, 45 mph or less).

ANOVA models for standard deviation of speeds at the taper (see Figure 4) indicated that speed variations increased significantly with both volume and truck levels. The early merging strategy resulted in the lowest observed speed variation, as did sites with a 45-mph speed limit. The latter was to be expected, since 100 percent compliance was assumed. These results tend to support the general concerns about the safety hazards associated with late lane changes (e.g., rear-end collisions). The problem of speed variation becomes even more acute at sites with short warning distances or with a large truck population.

The proportion of merges occurring prior to 400 ft (see Figure 5) from taper was found to decrease in a linear fashion with volume. Unexpectedly, however, the presence of trucks resulted in fewer late lane changes. It is suggested that the advantage truck drivers have in recognizing (hence responding to) the TCD outweighs the fact that trucks constitute a potential obstruction to following passenger cars. Of course, this interpretation considers similar responses from truck and passenger car drivers, a fact that could not be disproved from the driver survey results.

Merging strategy had a drastic impact on the frequency of free (as opposed to forced) merges (85 percent for early merging strategy versus 42 percent for late merging strategy). Furthermore, when an early merging strategy was coupled with a 1-mile effective warning distance, the proportion of free merges did not drop below 90 percent, even at volumes approaching the single-lane capacity.

Finally, the impact of speed-control strategies provided some revealing findings on the impact of reduced speed limits on merging in construction zones. When the 45-mph limit was in effect, the frequency of free merges was actually reduced by 15 percent compared with the no-speed-control strategy. It is suggested that since drivers are primarily concerned with maintaining safe headways in the open lane, a drastic speed reduction would in effect increase the traffic density near the transition zone. Consequently, the probability of finding acceptable gaps is reduced, hence the increase in the frequency of forced merges.

DISCUSSION OF RESULTS

This study was aimed at the investigation of merging and speed controls at freeway construction-lane closures through the use of computer-simulation techniques. A traffic model incorporating individual drivers' preference, traffic-stream descriptors, and characteristics of TCDs was developed. The model was field tested with varied results at two sites. The work is continuing on the refinement of the model.

The findings of this study may be summarized as follows:

1. The field-study results indicate that the effectiveness of the advance-warning devices at freeway construction-lane closures is not determined solely by the design features of the individual devices but also, and perhaps more importantly, by the risk perceived by approaching drivers. Under low-volume conditions, drivers' merging patterns and travel speeds are virtually unaffected by the advance-warning devices at the site. Speeds and/or lane changes are initiated only when the construction activity is actually in sight. At higher volumes, however, many drivers merge early.
2. The simulation-study results indicate that at sites experiencing approach volumes in excess of 1000 vph, it is desirable that early merging be encouraged. Traffic-engineering measures that deter travel in the closed lane (i.e., lane to be closed ahead) should be contemplated. A recent study (11) indicated that changeable message signs were quite successful in that respect.

The implementation of the 45-mph maximum speed control and assumed 100 percent compliance resulted in higher percentages of forced merges in the taper area in the model. The assumption of 100 percent compliance was not meant to be a realistic assumption, but it is still interesting to note that from the point of view of smooth merging, the speed reduction may not even be desirable.

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Selecting Two-Regime Traffic-Flow Models

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A procedure for selecting two-regime macroscopic models for a given set of traffic-flow data is presented. The procedure is based principally on the theoretical characteristics among the various regions of macroscopic models, which includes the limiting case and the convexity and concavity properties. The input to the procedure is represented by the basic traffic-flow criteria (free-flow speed, optimum speed, jam density, and so on) as well as auxiliary criteria to account for the variability of the traffic-flow relations in the intermediate ranges of flow. With these criteria, which are established from the data, the procedure can directly output model parameters, through simplified graphical tools, for the non-congested- and congested-flow regimes. Application of the procedure by using actual data was made to illustrate its use and to discuss some issues related to establishing the traffic-flow criteria from the data. This application also illustrates the flexibility of the procedure and the ease with which the specified criteria can be adjusted to further improve the data fitting. The procedure presented in this paper significantly reduces the need for using computer facilities in estimating traffic-flow relations and as such should prove useful in many transportation applications.

Macroscopic traffic-flow models have been widely used in the field of transportation, including freeway operations, highway levels of service, environmental studies, and transportation planning. Generally, these models can be used to describe the traffic-flow relations in two ways: single-regime and two-regime representations. In the former, the entire range of operation is represented by a single model, whereas in the latter, two models are used--one for the non-congested-flow regime and the other for the congested-flow regime. The idea of the two-regime representation was first proposed by Edie (1). The general macroscopic models, their estimation approaches, and the scope of this paper are discussed first.

GENERAL MICROSCOPIC AND MACROSCOPIC MODELS

The general car-following (microscopic) equation developed by Gazis and others (2,3) is given as follows:

$$\ddot{X}_{n+1}(t+T) = \alpha\left\{\dot{X}^{m}_{n+1}(t+T)/[X_n(t) - X_{n+1}(t)]^{\ell}\right\}[\dot{X}_n(t) - \dot{X}_{n+1}(t)] \quad (1)$$

where

$\dot{X}_n$, $\dot{X}_{n+1}$ = speed of leading and following vehicles, respectively;
$\ddot{X}_{n+1}$ = acceleration (or deceleration) rate of following vehicle;
T = time lag of response to stimulus;
α = constant of proportionality (referred to throughout as a model parameter); and
ℓ, m = model parameters.

By integrating Equation 1, the general form of macroscopic models has been developed by Gazis and others (3). By using this general form, a matrix of macroscopic models has been established for different combinations of ℓ and m parameters by May and Keller (4). This matrix has undergone some adjustments by Ceder (5) and by Easa and May (6). The final version of the matrix is shown in Figure 1, along with illustrations of its use for the two-regime representation.

Figure 1 shows the speed-density relations and consists of five regions. In regions 1 and 2, models have no intercept with the speed axis, $u_f \to \infty$. In regions 4 and 5, models have no intercept with the density axis, $k_j \to \infty$. Models in region 3 have intercepts with both the speed and the density axes. Single-regime representation is usually accomplished by using models from region 3. The two-regime representation can be made, as illustrated in Figure 1, by using models from regions 1, 2, or 3 for the congested-flow regime and from regions 3, 4, or 5 for the non-congested-flow regime.

ESTIMATION APPROACHES

Estimation of macroscopic models is an essential task. For a given set of traffic-flow data, one often needs to estimate model parameters that best represent these data. In this regard, an approach employing computer techniques has been developed by May and Keller (4). This approach uses regression analysis to estimate model parameters for specified values of traffic-flow and statistical criteria. These criteria include free-flow speed u_f, optimum speed u_0, jam density k_j, optimum density k_0, maximum flow q_m, and a mean-deviation criterion.

In an attempt to significantly reduce the need for using computer systems, another theoretical-graphical approach has been recently proposed and applied to the estimation of single-regime models (7). This approach is based principally on the theoretical relations among the first five criteria mentioned above and model parameters ℓ, m, and α. A simplified graphical tool was used to represent those relations and could directly provide model parameters that satisfy specified traffic-flow criteria. This approach was applied later to the estimation of a special case of two-regime models by Easa and May (6). The procedure that has been developed for estimating the single-regime models corresponds to region 3 and that developed for the two-regime models corresponds to regions 2 and 4 and in a preliminary fashion to region 3. In both pro-