FREEWAY DIGITAL SIMULATION MODELS

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This paper reviews 15 simulation models associated with various aspects of freeway vehicular traffic. They range from special-purpose programs directed toward studying the impact of trucks on the traffic flow to general-purpose programs that include most known variables of importance. The models are compared against a baseline of eight features that are regarded as both desirable and independent of specific simulation purpose. Most of these features typically represent characteristics that are of value to a potential user in making a choice as to which model would best serve his needs. Concurrently it is represented that these features could furnish a baseline to accomplish a certain amount of standardization. Each model is treated briefly in terms of these features and other special attributes. An overall comparison table is developed for easy reference as to the basic purpose and characteristics of each model.

•SIMULATION of vehicular traffic on digital computers has attracted considerable interest since the late 1950s. It began with the simulation of vehicles approaching and departing from isolated signal-controlled intersections. It was not until the late 1960s that digital simulation was applied to freeway traffic and related features.

A decade ago Gerlough (1) presented a detailed discussion on simulation techniques and what could be achieved toward improving traffic flow theory and practices by the application of digital computer simulation. Today, more than a dozen general-purpose or special-purpose freeway digital simulation models have been developed.

A careful examination of the existing models indicates that there was a lack of coordination in the development of models. There were no standards for the models and no application guidelines, which makes it difficult for the user to determine what model to select for his needs. Because of the lack of a universally accepted traffic flow theory and varying operational characteristics, each model was developed largely through intuition. Validation is a very expensive and time-consuming process, and no extensive validation covering a wide range of freeway geometrics and traffic patterns has been conducted on any model. Therefore, the realism and utility of the existing traffic simulation models are still doubtful.

These limitations do not imply that all of the model development effort was wasted. On the contrary, considerable fresh knowledge of traffic flow phenomena has been obtained through simulation. It is believed that further advancement in digital simulation can be achieved through a well-planned, coordinated effort.

The purpose of this paper, in addition to a review of existing simulation models, is to address the desirable characteristics and features of models. We hope to attract the attention of highway research personnel to the need for future standardization model development and documentation and provide summaries of existing models for those who want to select a model for their use but do not have the time to study each model's capabilities and limitations in detail.

The 15 models under consideration are

1. Arizona Transportation and Traffic Institute Traffic Simulation Model,
2. Midwest Research Institute Freeway Simulation Model,
3. Midwest Research Institute Mountainous Terrain Model,
4. Northwestern University Lane-Changing Model,
5. Sinha Freeway Simulation Model,

6. Connecticut Department of Transportation Expressway Simulation Model,
7. Texas Transportation Institute Freeway Merging Model,
8. System Development Corporation Diamond Interchange Model,
9. System Development Corporation Freeway Simulation Model,
10. Mikhalkin Freeway Simulation Model,
11. Georgia Model,
12. SCOT Corridor Model,
13. Priority Lane Model,
14. Aggregate Variable Models, and
15. Aerospace Corporation Freeway Simulation Model.

These simulation models varied in purpose and structure because of different user requirements. However, there are desirable general characteristics that each model should possess and other features that will add more application value to the model. They include

1. Realism for representing freeway flow phenomena,
2. Existing features built into models to handle anticipated applications,
3. Logic complexity,
4. Computer running efficiency,
5. Extent of model validation,
6. Flexibility and expandability,
7. Suitability for incident detection and ramp control, and
8. Completeness of program documentation.

The following sections give a detailed discussion of these characteristics and a critical review of each model with respect to them.

DESIRABLE CHARACTERISTICS

The eight characteristics and features mentioned certainly do not cover the complete spectrum of simulation models. They do, however, more or less reveal the value and capability of each simulation model.

Realism for Representing Freeway-Flow Phenomena

This characteristic reflects how closely a simulation model is able to describe traffic flow behavior, particularly when certain important freeway traffic components are neglected or some convenient assumptions are made to simplify the model.

Existing Features Built Into Models to Handle Anticipated Applications

Most of the 15 simulation models listed were developed with a single purpose in mind. The purpose for the individual models and existing features and capabilities are addressed later.

Logic Complexity

Because each model is developed for a different application, some have more features than others. In general, car-following and lane-changing are the two most important elements found in common. Because of space limitations, we shall not describe the logic in detail but rather overview the logic complexity of each model. A comprehensive summary of the car-following and lane-changing rules is given elsewhere (2).

Computer Running Efficiency

This refers to the ratio of computer time to simulated real-time freeway traffic. More accurately, it refers to the computer costs associated with the simulation per unit of real time. To compare strictly the efficiency of two different simulation models, simulation runs should be conducted under identical conditions of freeway geometry and traffic volumes. Since each model is developed for different purposes and has different freeway geometry, it is not possible to run them under identical conditions or to use reported results to compare the efficiency. However, by quoting the simulated condition and the running time plus the computer model and core size used, the reader will have some idea of the relative efficiency of each model.

Extent of Model Validation

Model validation is a time-consuming process that involves data collection, data reduction, and statistical analysis and testing. Validation of the models as a whole has been less than adequate, particularly in terms of statistical analysis and testing.

Flexibility and Expandability

The flexibility of the computer simulation model refers mainly to the structuring of the computer program in terms of facilitating the improvement or integration of the logic into a more general-purpose model. The expandability refers to the extension of a model to cover a more general freeway configuration or traffic flow conditions. Detailed discussion of flexibility and expandability of each model is difficult without a complete examination of program listing and documentation. These have not been obtained to date, and thus only general comments will be made regarding these aspects.

Suitability for Incident Detection and Ramp Control

A major use of traffic simulation models is to test the effectiveness of freeway surveillance and control strategies before they are implemented into an operational system. This avoids the expensive testing of ineffective strategies on-line. One important element in surveillance is the density and total number of detectors required to measure various traffic characteristics at specific locations so that the occurrence of freeway incidents can be identified. A counterpart in control is the provision of on-ramp signal-control capability so that the simulation model is able to test the effectiveness of different on-ramp control strategies.

Completeness of Program Documentation

All the simulation models except one were programmed in FORTRAN, but some models have subroutines written in lower-level languages. The exception is model 8, which is in JOVIAL. The extent of program documentation varies considerably from model to model. We shall rate the program documentation in three levels:

1. Availability of a user's manual in addition to comprehensive documentation. This will allow users unfamiliar with the program details to proceed step by step and complete a successful simulation run.
2. A comprehensive explanation of the program. This provides to users the detailed capability of the model and the structure of individual components of the model and thereby allows the user to visualize the possibility of program modification and expansion.
3. A brief explanation of the various routines of the model. This implies that program documentation is inadequate and therefore makes it difficult to evaluate the efficiency and usefulness of the model. It is to be noted that the completeness of program documentation is based on reports that are currently available.

Each of these points will be reflected in the following discussions of the individual models. Because program documentation is not prepared at the same level of sophistication, some characteristics of specific models are either unclear or completely unknown.

CHARACTERISTICS OF THE MODELS

Model 1—Arizona Transportation and Traffic Institute Traffic Simulation Model

This model was developed by Richard, Baker, and Sheldon (3) to simulate freeway traffic that may be used to establish freeway interchange design criteria. The freeway geometry is restricted to 3 through lanes, 1 ramp, and an acceleration lane or an auxiliary lane. However, with minor program changes, 1 and 2 through-lane systems may be simulated. Ramps are restricted to direct connections and loop connections. Freeway grade is handled in this study by changing both the operating speeds and the vehicle acceleration and deceleration rates. Simple logic for vehicle distribution among lanes, car-following, and lane-changing is provided.

In preparing simulation runs, freeway volume and ramp volume are specified. There are three alternatives in choosing vehicle processing time, starting from 1.5 seconds, with an increment of 1.5 seconds. Vehicles are generated from a binary decision rule within the review period according to the input volume. This gives essentially a negative exponential distribution. Desired speeds are generated from a normal distribution with modification for trucks and grades.

This model is probably flexible enough to allow some simple additional capabilities. Since the overall logic is very simple, it is doubtful that the model realistically represents traffic flow in any detail.

The model has not been validated and the simulations did not provide figures that related to running efficiency. The program is written in FORTRAN for use on an IBM 7072/1401 computer and requires 8K of core storage. A summary of the characteristics of this model as well as other models is given in Table 1.

Model 2—Midwest Research Institute Freeway Simulation Model

The purpose of this model (4, 5) is to assist in the design of interchanges by providing a method for assessing the efforts of design variables on traffic capacity, safety, and level of service. Special emphasis is therefore placed on traffic flow in the vicinity of entrance and exit ramps.

The freeway section can be up to 80,000 ft long, with 2 to 4 through lanes and up to 6 right-hand and 6 left-hand ramps (a maximum possible total of 12 ramps). The ramps can be any combination of on- and off-ramps located arbitrarily along the freeway section. Any or all of the on-ramps can be equipped with traffic signals, and therefore the model is capable of testing ramp control strategies.

The simulation vehicles are designated by driver type, vehicle type, desired speed, and cooperator, which indicates that the vehicle will oblige would-be lane changers by trying to provide a usable gap in front. The volumes are specified for each lane and ramp.

The car-following and lane-changing logic is very complex. The acceleration and deceleration capabilities are reflected by vehicle types. Vehicles are generated in a fashion similar to those in model 1 but with the application of different weights for the red and green periods to the ramps. Desired speeds are generated from truncated normal distributions. The review time period is 1 second, which is shorter than that of model 1. Under this processing time interval it would typically require 20 minutes of computer time on an IBM 360/50 per minute of simulated time to simulate 1 mile of freeway with 3 lanes in 1 direction with an average traffic density of 45 vehicles/mile/lane.

The program is written in FORTRAN IV, with a few subroutines written in assembler language. The model has not been validated. The program documentation is adequate.

Model 3—Midwest Research Institute Mountainous Terrain Model

This model (6) was developed to study traffic characteristics on 4-lane divided highways in mountainous terrain. The geometric configuration of the model allows simulation of a freeway section up to 131,000 ft long with the 2 lanes and an intermittent right climbing lane. There is no provision for on- or off-ramps. The grade and the front and rear sight distances are defined for the entire section. Different vehicle characteristics are also defined, and curve-limited or downgrade-limited maximum speeds may be specified within certain zones.

Most simulation dynamics are the same as those of model 2 except where the desired speeds and acceleration capabilities are functions of grades and horizontal curvature.

Validation was performed at two levels, the microscopic and the macroscopic. The former includes vehicle performance characteristics, car-following behavior, and gap

Table 1. Summary of the 15 models.

Model No.	Purpose	Freeway Geometry	No. of Ramps	Vehicle Generation	Desired Speed Distribution	Simulation Dynamics	Grade and Curvature Effect	Valida-tion	Ramp Signal Capability
1	Ramp design criteria	Straight section, 3 lanes	1	Negative exponential	Normal for both freeway and ramp	Lane distribution logic, car-following and lane-changing	Grade effect included	None	None
2	General purpose	Straight section, up to 4 lanes	6 right, 6 left	Negative exponential	Truncated normal	Complex car-following and lane-changing rules	None	None	Yes
3	Mountainous road	Mountainous terrain	None	Negative exponential	Truncated normal	Complex car-following and lane-changing rules	Yes	Yes	None
4	Lane-changing	Straight section	None	Shifted exponential	Normal	Car-following and simple lane-change and gap-acceptance logic	None	Very little	None
5	General purpose	Straight section	4 on, 6 off	Freeway, shifted exponential; ramp, hyper-Erlang	Normal	Car-following and lane-changing, merging	None	Yes	None
6	Design tool	Straight section	10 on, 10 off	Negative exponential	Near normal from field data	Simple car-following and lane-changing rules	None	Yes	None
7	Merging	Straight section	2 off, 6 through and on	Poisson	Truncated normal	Simple car-following and lane-changing logic but extensive ramp merging logic	None	Very little	Yes
8	Diamond interchange design and operation	Diamond interchange	1 on, 1 off	Truncated exponential	None	Microscopic on arterial and macroscopic on freeway	None	Yes	Yes
9	General purpose	Arbitrary network	Unlimited	Negative exponential	None	Car-following, lane-changing, merging	None	None	None
10	Freeway surveillance	Straight section	None	Not available	Truncated normal	Car-following, lane-changing, sensor simulation	None	Yes	None
11	Truck behavior	Straight section	Not available	Shifted exponential	Normal	Car-following, lane-changing, ramp merging	None	Yes	None
12	Freeway corridor operation	Freeway corridor	Not available	Not available	Not available	Macroscopic on freeway and microscopic elsewhere	None	Yes	Yes
13	Priority lane	Straight section	50	Not available	Not available	Compressible fluid	None	Yes	None
14	Ramp control	Straight section	Not available	Not available	Not available	Continuum model	None	Yes	Yes
15	General simulation	Arbitrary network	Unlimited	Poisson	Normal	Car-following, lane-changing, ramp merging, collision	Yes	Yes, but no statistical test	None

Model No.	Detector Capability	Starting Mechanism	Warm-Up Time	Maximum No. of Vehicles Allowed	Computer	Programming Language	Core Requirement	Computer Time/Simulation Time Ratio	Documentation
1	None	Not available	Not available	Not available	IBM 7072/1401	FORTRAN plus Autocoder statements	8K	Not available	Poor
2	None	Empty	Not available	3,000	IBM 360/50	FORTRAN IV plus 2 subroutines in assembler	Not available	20:1	Good
3	None	Preloaded	Not available	Not available	CDC 6400	FORTRAN IV plus assembler for 1 subroutine	32K (60 bit)	20:1 to 10:1	Good
4	None	Empty	Not available	300/lane	CDC 6400	FORTRAN IV plus SPURT simulation language	Not available	1:4 to 1:20	Poor
5	None	Preloaded	Not available	800/lane	IBM 360/65	FORTRAN IV plus assembler	110K bytes	1:2 to 1:10	Fair
6	None	Empty	Not available	1,000 at any time	Univac III	FORTRAN IV	30K (24 bit)	3:1	Poor
7	None	Preloaded	1 minute	500 at any time	IBM 7094 Model I	FORTRAN IV	Not available	Not available	Poor
8	None	Preloaded	15 minutes	2,000	IBM 360/67	JOVIAL plus machine language	60K	1:75	Poor
9	Yes	Preloaded	15 seconds	2,500	IBM 360/67; Univac 1108	FORTRAN IV	65K (36 bits)	1:1 to 5:1	Poor
10	Yes	Preloaded	Not available	Not available	IBM 360/144; 360/67	FORTRAN IV	120K bytes	4:1	Fair
11	None	Preloaded	None	Not available	IBM 360	FORTRAN IV plus BAL	Not available	0.5:1 to 0.75:1	Fair
12	None	Not available	Not available	Not available	Not available	FORTRAN IV	213K bytes	Not available	Fair
13	None	Not available	Not available	Not available	CDC 6400	FORTRAN IV	Not available	Not available	Fair
14	None	Not available	Not available	Not available	IBM 360/44	FORTRAN IV	Not available	1:11	Poor
15	None	Not available	Not available	Unlimited	CDC 7600	FORTRAN IV and COMPASS machine language	100K (60 bit) est., 8,000 statements	1:7	Poor

acceptance in lane change. The latter considers gross flow characteristics such as flow to lanes, lane change frequencies, spot speed distributions, time headways, and overall travel speeds. Reported validation involves the comparison of real-world data from other studies to simulations using the model. Continuing efforts are being conducted as more extensive validations of platoon behavior and passing logic using newly collected photographic data taken near Pacheco Pass on California Route 152 and Topanga Canyon on California Route 23.

Program documentation is extensive and includes a comprehensive user's manual, but the program listing is not available. Because of the detailed logic and good validation results the model is believed to possess sufficient realism for its purpose. However, the model is not very efficient. Reported simulation runs have a ratio of computer time to simulated time in the order of 20:1 to 10:1 using a CDC 6400. The program is written in FORTRAN IV except for one short subroutine in assembly language. It requires 32K words of computer memory.

Model 4—Northwestern University Lane-Changing Model

A detailed examination of freeway lane-changing behavior was the motivation for developing this model by Worrall and Bullen (7). For this reason the freeway geometry is limited to a 4-lane straight section without ramps. The simulated freeway length can be up to a few miles.

The car-following logic is fairly complex. The lane-changing logic is based on a lane-changing desire flag for each vehicle and the available gap. Vehicles are generated from a shifted negative-exponential distribution with desired speeds chosen from a normal distribution. The model produces output showing lane frequencies, lane-change delays, vehicle redistribution, etc., but does not accept a mix of vehicle types. The computer running efficiency of the model is relatively high, the computer-time to simulated real-time ratios ranging from 1:4 to 1:20 for 2-, 3-, and 4-lane situations with volume ranging from 600 to 1,800 vehicles/lane/hour. The flexibility of the model is fairly high, although the relative ease with which the model can be recalibrated is not. Lane-changing frequency and speed-volume outputs of the model match favorably with field data collected at various Chicago freeways.

The model is programmed in FORTRAN IV for a CDC 6400 computer, with some subroutines written in SPURT simulation language developed at Northwestern University. Only a small-scale calibration has been made on the model. Program documentation consists of a brief description of the various routines and a program listing.

Model 5—Sinha Freeway Simulation Model

This is a general-purpose simulation model developed by Sinha (8, 9) for use as a tool in the analysis of freeway phenomena. The model has a capacity for the simulation of 5 lanes, 4 on-ramps, and 6 off-ramps. The ramps may be located either on the right-hand or left-hand side of the freeway. It can simulate up to 3½ miles in length using a 256K IBM 360/65 system.

The car-following and lane-changing logic is fairly complex. The gap-acceptance logic is similar to that of model 7. Only two types of vehicles are assumed. Freeway mainline traffic was generated from a shifted exponential distribution, while ramp vehicles were generated from a hyper-Erlang distribution. Desired speeds were generated from a normal distribution.

Because the model was developed as a general-purpose tool for analyzing traffic operating characteristics, the computer output provides detailed information at each of the several control points (points of interest):

1. Distribution of headways in each lane,
2. Distribution of speeds in each lane,
3. Distribution of traffic volumes in each lane,
4. Distribution of exiting, entering, and through vehicles, and
5. Distribution of exiting, entering, and through vehicle speeds in each lane.

The computer program is written in both FORTRAN IV and IBM 360 assembler language for an IBM 360/65 computer. The review period is 1 second. However, the core requirement is not given. A maximum of 800 vehicles can be processed for each lane. Reported simulation results show the ratios of computer time to simulated time vary from 1:2 to 1:10.

Data for model validation were from the Eisenhower Expressway in Chicago, the Long Island Expressway in New York, and the 1965 Highway Capacity Manual. Program documentation consists of a good description of the main program and subroutines plus program listing.

Model 6—Connection Department of Transportation Expressway Simulation Model

The Connecticut model (10) is similar to model 1 and was also developed for the purpose of investigating, evaluating, and solving freeway design problems. It allows a 5-mile, 7-lane section with 10 on-ramps and 10 off-ramps. On-ramps are restricted to direct connections. It can handle 1,000 vehicles in the system during any given second.

Driver characteristics include the assignment of acceptance gaps to individual vehicles, desired speeds from a near-normal distribution based on field data, the generating of vehicles similar to that of model 1, and the acceleration and deceleration capability as linear functions of speeds. The car-following and lane-changing logic is very simple as compared to most of the other models.

The reported computer running efficiency of this model is about 3 minutes of computer time for every minute of real time on a Univac III. The program is written in FORTRAN IV with a requirement of 30K (24 bits) words of core storage. Program documentation was not available at the time of preparing this paper.

The model was validated by using the chi-square and Kolmogorov-Smirnov test to compare the simulation results with data on speed and headway distributions from the 1965 Highway Capacity Manual.

The chi-square test yields a confidence level for a cell-by-cell comparison of two distributions while the Kolmogorov-Smirnov is a nonparametric test of the maximum difference between two accumulative distributions. For the three volumes investigated, i.e., 1,000, 1,500, and 1,800 vehicles per lane, the chi-square test showed a level of confidence of 85, 90, and 95 percent respectively, while the Kolmogorov-Smirnov test showed a confidence level of 95 percent for all three volumes.

Model 7—Texas Transportation Institute Freeway Merging Model

This model was developed by Buhr et al. (11) for the purpose of simulating traffic operations under different modes of on-ramp control. The number of off-ramps is limited to 2, while the number of entrance ramps plus freeway lanes is limited to 6, with a maximum freeway length of 6,000 ft.

During simulation road sections must be preloaded. New vehicles are generated from a Poisson distribution. Each vehicle is assigned a number of characteristics such as length, current speed, desired speed, and distance from the zero reference point (beginning of the simulation section). The desired speed is generated from a normal distribution, but, if the generated speed is higher than the designated maximum speed, it is then reduced to the maximum speed. The simulation program consists of one monitor routine and 16 subroutines. Each subroutine is completely modular so that any logic changes in any subroutine will not affect the remainder of the program. The various ramp control modes the model can handle include (a) no control, (b) fixed-time metering, (c) demand-capacity metering, and (d) gap acceptance control. The computer scan time is 1 second. Besides rather simple car-following and lane-changing logic, the model provides extensive ramp merging logic for the purpose of testing the various ramp control strategies.

A simple validation study was performed using the geometrics and data of the outbound Cullen on-ramp on the Gulf Freeway in Houston. However, no statistical tests were conducted to indicate the level of confidence.

The computer running efficiency was not reported. The program is written in FORTRAN IV for the IBM 7094 Model I computer. Complete program documentation is not available.

Model 8—System Development Corporation Diamond Interchange Model

This is one of the only two models among the 15 that have both the microscopic and macroscopic features built into the model. This model, developed by Nemeczky and Widdice (12) as a tool to aid in the design and operation of signalized diamond interchanges, contains both freeway and signalized arterial submodels, the freeway section being limited to 2 on- and 2 off-ramps.

The program logic is fairly complicated in terms of a macroscopic model. Vehicles are generated from a truncated exponential distribution to eliminate the possibility of unusually large time headways, and five driver types were allowed.

Since the model was developed to evaluate selected operational or design alternatives, the following outputs were provided:

1. Average travel time through the system,
2. Average travel time through each individual model region,
3. Average speed through the system,
4. Average speed through each individual model region,
5. Average delay through the system,
6. Average delay through each individual region,
7. Number of stops, and
8. Acceleration noise.

The model allows inspection of changes of a diamond interchange geometry (full, split, or partial diamond, changes in through and turning lanes and pockets, etc.) as well as the change in signal control parameters. Model validation was conducted by comparing the simulation outputs of the number of cars through the system and through each section of the model by origin-destination and the travel times by origin-destination with data collected at the Coldwater Canyon diamond interchange of the Ventura Freeway in Los Angeles. The Wilcoxon signed-rank tests indicated the model was valid at the 5 percent level of significance.

Model 9—System Development Corporation Freeway Simulation Model

A series of general-purpose freeway simulation models were developed in the order of increasing complexity. Here we shall discuss only the most recently developed one (13) because it is the improved and generalized version of all its predecessors. A unique feature of this model is that multilane highways were modeled by circular tracks. This creation generated many advantages in the simulation. The model is considered very general, so that any reasonable freeway configuration (including freeway interchanges) can be modeled. The network size is limited primarily by the number of cars that can be handled. For a 65K core (36 bits) computer the number is 2,500 cars.

The model provides extra capabilities such as the generating of position-time plots, and its structure allows direct simulation of sensors, controls, and control algorithms. The logic is not complicated in terms of the capabilities it provides.

The position-time plots could be viewed as a computer-generated movie, so that it is easy to bring out the turbulent aspects of the overall flow or so that one can focus on the behavior of individual vehicles to determine the realism of the simulation logic.

The model advances roughly 500 cars in 1 minute of computer time for 1 minute of real time on a Univac 1108. It is expected, with some modifications, that 15 minutes of Univac 1108 computer time will allow 5,000 cars to be advanced for 3 minutes of simulation time.

No validation has been done on the current version, but limited validation performed on an earlier version of the model included the comparison of flow-concentration data obtained from the simulation with data collected on a 2-lane expressway in Virginia. Program documentation has not been prepared at the present time.

Model 10—Mikhalkin Freeway Simulation Model

The model, developed by Mikhalkin (14), provides a means for systematic experimentation with the capability of controlling factors of the driver-vehicle-roadway system that usually cannot be controlled in real traffic flow. The simulated roadway is a straight, level freeway with no ramps, up to 4 lanes wide and 20,000 ft long, and with sensors. Simulation is on the IBM 360/65 system with 120K core storage. However, this restriction can be easily removed if larger core size is available.

Simulation can begin at a high concentration, low concentration, or even an empty system. The scan interval is 0.75 second, which is equivalent to the driver reaction time in the model.

The car-following logic is based on the nonlinear car-following rule of Gazis et al. (15), and the lane-changing logic is based on that of model 4. Detectors were simulated in the model to provide volume and occupancy measurements. The sensor sampling rate was 15 per second. Procedures for estimating the roadway local density and space mean speed from detector measurements were developed with a high degree of accuracy. Vehicles were generated randomly, but no specific distribution was mentioned. Vehicle desired speeds and vehicle lengths were obtained from truncated normal distributions whose parameters were input data.

Because of the various traffic parameter estimating algorithms implemented in the model that use detector-measured data, this model is extremely useful for freeway surveillance and incident-detection purposes.

The model was written in FORTRAN IV and is modular in form so that each routine can be easily modified. The computer running efficiency is low—of the order of 4 units of computer time to 1 unit of simulated real time for a 4.6-mile section of a 4-lane freeway.

The model validation was based in part on the similarity in form and magnitude of the flow-concentration relationships obtained from the simulation and published data. Although good agreements were reported, no statistical tests were conducted to justify the observations. However, extensive statistical work was performed on sensor simulation.

Model 11—Georgia Model

The Georgia model developed by Wildermuth (16) was primarily concerned with the assessment of truck effects on freeway flow characteristics. Model development was based on an extensive evaluation of models 2, 4, and 7. Successful components from the earlier models were adapted and modified so that trucks could be properly introduced as a distinct element into the traffic flow simulation.

The basic structural elements of the Georgia model closely resemble those of model 4. Each vehicle is associated with a vector containing 12 specific characteristics such as the desired speed, current speed, and vehicle type. Vehicles are generated from a shifted exponential distribution. The desired speed is generated from a normal distribution, with the mean and standard deviation as separate input variables for each lane.

Simulation starts with a preloaded condition without requiring a warm-up time to achieve a stable flow.

Model validation was done in terms of comparing the generation of different vehicle types, headway distributions, lane volume, speed distribution, and lane-changing frequencies from the simulation runs to those of the real data, and good results were shown.

For a 1-mile freeway section with 3 lanes, simulation times on an IBM 360/30 computer ranged between 2.4 and 3.0 times the simulated real time depending on the traffic volume. It is expected the ratio will be 0.5 to 0.75 on the IBM 360/50.

The model was written in FORTRAN IV, with several minor routines in assembly language. A complete program documentation is not available, but instructions on running the model are given.

Model 12—SCOT Corridor Model

The SCOT (simulation of corridor traffic) model (17) was originally conceived as a concatenation of two existing models—the UTCS-1 simulation model of urban traffic (18) and the DAFT simulation model of freeway traffic (19). The SCOT model is also a dual microscopic (the UTCS-1) and macroscopic (the DAFT) model like model 8.

The SCOT model treats vehicles microscopically on the arterial street system (including ramps) and macroscopically (as platoons) on the freeway. Any arbitrary freeway and surface street network containing up to 200 intersections may be represented, and traffic flow is described by specifying either origin-destination volumes along the peripheral entry links or turning movements at each node.

The objective of developing this model was to use it as a medium for assisting in defining the surveillance and control requirement for both existing and planned freeway corridors.

The crux of the freeway component of the SCOT model is the speed-density formulation resulting from a general form of the non-integer car-following rule by Gazis et al. (15). The unknown parameters of the speed-density equation have to be determined experimentally before the simulation run.

Complete program documentation, including a user's manual, is available. However, the description of the system is poor as compared to other model documents, and therefore much key information such as detailed system capability and computer running efficiency does not appear in the system's description.

Model validation consists of a comparison of simulation on a 0.4-square-mile network in Dallas containing two short freeway sections to the aerial photographic field data; good agreement is shown.

Model 13—Priority Lane Model

This model (20, 21) was directed toward evaluating traffic operations on freeways with priority lanes such as those allocated for buses or vehicles containing a required minimum number of passengers. The model geometry allows a maximum of 50 freeway subsections, with not more than 1 ramp in each subsection.

The model logic is sophisticated and efficient. It is essentially macroscopic, with input data provided for each 15 minutes. The computer program has a modular structure, and additional capability can easily be obtained by modifying or including the appropriate subroutines. Future changes can be made with minimum effort to match model results with empirical data. Running instructions and input data formats are provided for using the model.

The model idealizes physical queues, and this may obscure some of the effects being studied. Furthermore, subsection capacities and demand are assumed to remain constant over 15-minute time slices. The study section is limited to 10 miles, and no off-ramp queuing calculations are attempted if off-ramp demand exceeds ramp capacity. Otherwise the model affords sufficient realism for representing traffic flow on freeways with any kind of priority lanes or reversible lanes and for ramp control schemes for priority vehicles. Validation of earlier versions of the model was made with data collected on the San Francisco-Oakland Bay Bridge, where vehicles with at least 3 passengers (to encourage the formation of car pools) were allowed the use of a faster-moving priority lane.

The computer program is written in FORTRAN IV for the CDC 6400 system.

Model 14—Aggregate Variable Models

In the aggregate variable models developed by Payne (22), a freeway is partitioned into sections and the freeway traffic is described by a set of dynamic equations in terms of the aggregate variables of flow rate, section density, and section speed. The purpose of the models is to study the problem of developing ramp control strategies with a high simulated real-time to computer-time ratio. The model does not distinguish flow by lanes, and the traffic flow is described as an extension of the simple continuum models. However, it seems that the model produces good results for ramp control purposes.

Except for a listing, no program documentation is available. The program is written in FORTRAN IV for IBM 360 computer systems. The computer running efficiency is high because of the macroscopic nature of the model—80 seconds of computer time on an IBM 360/44 for simulating 3 hours of real time for a 4.6-mile stretch of 4-lane freeway. The logic employed is relatively simple, and program flexibility appears to be poor. Model validation consists of a crude comparison between simulated results and data collected on a 4.6-mile section of the Hollywood Freeway in Los Angeles with 9 on-ramps, 7 off-ramps, and fixed-time (time-of-day) ramp metering.

Model 15—Aerospace Corporation Freeway Simulation Model

This very general model developed by Harju et al. (23) is capable of simulating any freeway network. A special feature of the model, similar to model 9 of System Development Corporation, is the capability to produce computer-generated traffic flow movies of any specific subarea of the network under simulation. The movies appear as stationary overhead aerial shots and can be used for detailed flow analysis, for program debugging, and as an aid during the validation process. The simulation is microscopic, with random assignment of individual driver attributes. Other features include introducing any type of traffic control system, simulation of individual collision situations, and grade and curve effects.

The model can accept any freeway road configuration under any possible traffic condition for up to 50 miles of a 4-lane freeway. The car-following, lane-changing, and off-ramp exiting logic used is relatively simple as compared to other microscopic types of models. The on-ramp gap-acceptance merge algorithms are much more complex; on-ramp configurations allow merging with or without an acceleration lane or with an auxiliary weaving lane connecting adjacent on- and off-ramps. The model also allows lane restrictions to be specified (trucks to remain in right lane; bus expressway lanes). The computer program is written in FORTRAN IV with the exception of a group of small machine-language (COMPASS) routines for fast data packing and unpacking. The computer running efficiencies for the freeway sections simulated vary from a computer-time to simulated-time ratio of 1:7 for a 2-mile, 4-lane section with 1 on-ramp and 1 off-ramp, a flow of 6,000 vehicles/hour, and a 1-second scan interval to 1:0.75 for a 6.5-mile section of the Los Angeles Hollywood Freeway with 8 on-ramps and 7 off-ramps, a maximum flow of 8,400 vehicles/hour, and a ½-second scan interval, on the CDC 7600. Model validation includes the following:

1. Time-headway study based on data collected on the Eisenhower Expressway in Chicago;
2. Passenger-car velocity distributions at different lane volumes, using results published in the 1965 Highway Capacity Manual;
3. Off-ramp exiting behavior based on data collected by the Institute of Transportation and Traffic Engineering, UCLA, at the White Oak off-ramp on the Ventura Freeway in Los Angeles; and
4. Merging and weaving studies to test the capability of the merge algorithm based on freeway and ramp volume data collected on a 4.1-mile section of the Hollywood Freeway in Los Angeles.

Although this model possesses many desirable features, there is insufficient program documentation for more detailed evaluation.

A summary of the 15 models is given in Table 1 for a clear-cut comparison of each model's capability and structure.

CONCLUSIONS AND RECOMMENDATIONS

As we have seen from the foregoing, each model has its own merit and may be uniquely qualified for a particular application. One prime consideration in simulating large sections of freeway is the computer costs involved. To this end, separate special-purpose models may have an edge on general-purpose models. For example, a model developed for the purpose of incident detection could be much simpler and more economical than a general freeway simulation model. Such a simple model would be one that includes only the characteristics relevant to the occurrence of an incident.

However, it is desirable for individual special-purpose models to be modular and compatible to each other so that they can be put together to simulate a variety of operational practices. This is the place where, without standardization, the adaptation can hardly be achieved.

A general-purpose simulation model should have the following features:

1. Unrestricted freeway geometry, or a collection of geometrics so that the right one can be selected for each simulation.
2. Simple car-following roles. Different rules may be required for free-flow and constraint-flow regions. Lane densities under 20 vehicles/mile would constitute the free-flow region where traffic is sparse and vehicles behave essentially independently of one another. A mean free-flow speed would be specified in this region.
3. Simple lane-changing logic that needs only to be statistically valid. A good example is the logic implemented in model 4. The simplicity of the car-following and lane-changing logic requirement is mainly for the gain of computer running efficiency.
4. Ramp control capability, so that different control strategies can be tested and evaluated.
5. Merging algorithms, cooperation with merging vehicles, and driver accommodation to temporarily accept low headways. Separate subroutines are provided for each of these features in model 2.
6. Varied vehicle characteristics, to distinguish between passenger and commercial vehicles. Many existing models provide such variety.
7. Varied driver characteristics.
8. Lane restrictions. This would include priority lanes as in model 13 as well as other restrictions as discussed in connection with model 15.
9. Incident generation procedures. This feature would allow the model to simulate and detect an incident.
10. Simulation of vehicle sensors at various freeway locations, as discussed in model 10. This feature is of particular interest in freeway incident detection.
11. Grade and curvature effect and weather and environment effect. This allows the model to adjust its parameters due to changes in these factors.

There may exist some other important features that need to be included. A complete list of requirements can be reasoned only after a careful investigation of the needs and an in-depth discussion with highway personnel. If each component can be built modularly and tested separately, then it is a simple matter to add more components to the general-purpose simulation model as the need arises.

Therefore, we can use any general-purpose simulation model such as model 9 or model 15 as a framework to modularize its individual components and include all the required capabilities. The resulting model is thus flexible, expandable, and economical to use. Furthermore, the computer program should be written in a high-level language such as FORTRAN that is suitable for execution in any general-purpose computer, and it should be well-documented so that it can be widely used with minimum effort.

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