APPLICATION OF SIMULATION MODELS IN TRAFFIC MANAGEMENT OPERATIONS

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INTRODUCTION

Many urban highway systems contain congested segments during peak traffic periods. When this congestion occurs, other portions of the highway system can be adversely affected by (1) reducing productivity; (2) reducing user level of service; (3) increasing accidents; (4) increasing air and noise pollution; and (5) increasing energy consumption.

Congestion occurs when vehicular demands exceed roadway capacities on some segment of the system for some periods of time, often when adjacent time periods and parallel alternate routes are not congested. To eliminate congestion and its adverse effects, two solution approaches (or their combination) are available: increase roadway capacity or reducing vehicular demand.

Simulation models are needed for the cost-effectiveness evaluation of operational schemes because of system complexity and the large number of alternatives to be investigated. The challenge to the model builder is that on the one hand the model should be easy-to-understand, easy-to-use, and fast, while on the other hand the model should give accurate and realistic results.

This paper describes the evolutional development of a series of freeway simulation models at the Institute of Transportation and Traffic Engineering, University of California, Berkeley, over the past eight years. The paper is presented in five parts: Early Traffic Models, Freeway Simulation Models, Freeway Decision Models, and Freeway Corridor Priority Entry Models, and Current Research.

The early traffic models combined flow models with queueing models and were directed toward investigations of reversible lane operations and exclusive bus lane operations. A comprehensive and flexible freeway simulation model was then developed which has become the central main component of later, more comprehensive models. The freeway decision models extended the freeway simulation model by including search procedures for determining optimum redesign and/or ramp control strategies. The two latest models are decision models for freeway corridor control and priority-entry control. The freeway corridor model combines the earlier developed freeway simulation model with a surface street model and collectively a search procedure leads toward an optimum intersection and ramp control strategy. The freeway priority-entry model combines the earlier developed freeway simulation model with a search procedure for determining optimum ramp control on a vehicle-basis or a person-basis. Continued research is currently underway.

The paper is intended for model-builders and traffic managers. Model-builders may find special interest in the evolutionary-aspects of this work and the continued effort to balance between simplicity and realism. Traffic managers may find special interest in the availability of these models and their application to real-life situations.

EARLY TRAFFIC MODELS

A traffic model normally consists of a flow model which handles nonqueueing situations and a queueing model which handles queueing situations. The first two parts of this chapter will briefly discuss the development of flow models and queueing models. This will be followed by a description of their integration into traffic models directed toward investigations of reversible lane operations and exclusive bus lane operations.

Flow Models

In nonqueueing situations, each roadway section can be assumed to be independent of abutting sections and adjacent time slices. If one knows the flow level (vehicles per unit of time), the speed and travel time can be estimated from a flow speed-density model (referred to in this paper as a flow model). Much research has been undertaken in the development of flow models[1]* and the ITTE work described here is only a small part of the total effort.

A so-called noninteger car-following model[2] was developed in 1967 which had the microscopic form:

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

where

X = distance position of vehicle

$\dot{X}$ = vehicle velocity

$\ddot{X}$ = vehicle acceleration (or deceleration)

n = lead vehicle

$n + 1$ = following vehicle

α = constant

t = instant of time

Δ = time lag

m,ℓ = model parameters

By selecting values for the model parameters, m and ℓ, and integrating almost all known flow models can be identified. In addition, the entire family of flow models can be identified by selecting noninteger as well as integer values for m and ℓ.

Additional work was undertaken to investigate single-regime and two-regime flow models[3,4] and flow-speed-density data sets from 44 field locations were investigated with the m, ℓ flow model. Consistency tests of the m, ℓ models results by day of week and year were undertaken[5] for three field locations along the Santa Monica Freeway.

The results indicate that the Greenshields flow model is as good as other integer single-regime models. The single-regime flow model can be improved by selecting non-integer values with m lying between 0.5 and 0.8 and ℓ lying between 2.2 and 2.8. The superior flow model is a two-regime model with a discontinuity near the maximum flow situation.

Queueing Models

In queueing situations, each roadway section cannot be assumed to be independent of abutting sections and adjacent time slices. Thus the analysis must include a length of roadway over an extended period of time. As with flow models, much research has been undertaken in the development of queueing models[1], and the ITTE work described here is only a small part of the total effort.

A deterministic queueing model was developed in 1966[6,7] in which the main assumptions are that the bottleneck capacity remains constant over time while the traffic demand has a trapezoidal-shape over time. Note that a rectangular-shaped demand pattern and a triangular-shaped

*Raised numbers in brackets refer to references contained in the bibliography.

demand pattern are subsets of a trapezoidal-shaped demand pattern. Such queueing characteristics as total delay, queue time, number of vehicles delayed, maximum and average individual delay, and maximum and average queue lengths are determined for each bottleneck investigation.

The deterministic queueing model has been applied to the Oakland Bay Bridge to determine the effect of capacity-change on queueing characteristics. The capacity-changes investigated included capacity increases due to design and/or control, and capacity reductions due to accidents.

Field measurements of capacity, demand, and queueing characteristics were obtained, and the model assumptions and results compared favorably with these field measurements. It should be noted, however, that the Oakland Bay Bridge has simplifying characteristics such as a single entrance, a single exit, and contains essentially one bottleneck.

Initial Traffic Models

As mentioned earlier, a traffic model normally consists of a flow model and a queueing model. In 1968[8,9], the Greenshields type flow model was combined with the deterministic type queueing model for the investigation of reversible lane operations and exclusive bus lane operations. Again, the study site was the westbound Oakland Bay Bridge and consisted of one bottleneck at the entrance to the bridge and the bridge itself[10, 11, 12].

The measure of effectiveness in each model is the change in total passenger time due to the proposed operational improvements. For added clarity, consider the exclusive bus lane model and the following equation.

$$\Delta TPT = TPTN - (TPTB + TPTC) \qquad (2)$$

where

TPTN = total passenger time for all vehicles under normal operations

TPTB = total passenger time for bus passengers in the exclusive bus lane(s)

TPTC = total passenger time for car passengers in the exclusive car lanes

ΔTPT = change in total passenger time due to exclusive bus lane operations.

The model was developed in modular structure and contains five major steps as outlined below.

Step One - Select one of three states -- normal operations, exclusive bus lane operations, or exclusive car lane operations.

Step Two - Calculate demand and capacity for state selected in step one above, and compare. If demand $\leq$ capacity go to flow model described in Step Three. If demand > capacity go to queueing procedure described in Step Four.

Step Three - Calculate unit trip time from volume/capacity rates, and determine total passenger time by multiplying unit trip time by appropriate factors of route length and number of passengers.

Step Four - Calculate queueing delay from deterministic queueing model, modify demand pattern downstream of bottleneck, calculate travel time from flow model, and add queueing delay to travel time.

Step Five - Repeat Steps One through Four until all three states are analyzed. Use equation (2) to determine measure of effectiveness.

FREEWAY SIMULATION MODEL

The need for a more comprehensive freeway model was recognized because of the assumption limitations of earlier models. The most significant requirements for the new model were the following:

1. Traffic demand could change over distance, and greater flexibility of demand changes over time.
2. Roadway capacity could change over distance, and capacities of ramps, merge areas, diverge areas, and weaving sections be considered.
3. Each roadway segment could have its own flow model.
4. Queueing over space should be considered and special recognition given to queue collisions and queue splits.

The model structure, computer program, and model application are described in the next three subsections. Three generations of the FREQ model have been developed [13, 14, 15].

Model Structure

The structure of the freeway simulation model (henceforth referred to as the FREQ3 model) can best be described by considering a distance-time diagram. The horizontal scale is distance with traffic flowing from left to right. The directional freeway section is divided into subsections with subsection boundaries being established at locations where demands and/or capacities change. The vertical scale is time of day and is divided into equal time slices. A cell is defined as having a length of one subsection and a time interval of one time slice.

The design features of the various subsections are translated into capacities, and these capacity values, c_{it}'s can be thought of as flowing upward through the distance-time diagram. The origin to destination demand tables (one for each time slice) are translated into subsection demands and these demands, d_{it}'s, can be thought of as flowing to the right through the distance-time diagram. Initially, it is assumed that there are no bottlenecks, but later this is checked, and if necessary, is automatically corrected

The procedural analysis of FREQ3 begins with the cell in the lower left hand corner of the distance-time diagram. The cell represents the furthest upstream subsections in the earliest time slice. Then the cells immediately to the right are analyzed until all cells in the first time slice have been analyzed. Then the cell which represents the first subsection during the second time slice is analyzed, followed by analyzing the cells immediately to the right. This procedure is continued from time slice to time slice, until all cells are analyzed.

The analysis in each cell consists of comparing the c_{it} value with the d_{it} value. Two outcomes are possible: either $d_{it} \leq c_{it}$ or $d_{it} > c_{it}$. If $d_{it} \leq c_{it}$, then this subsection in this time slice is not a bottleneck, and the flow, v_{it}, is equal to d_{it}. The flow-capacity ratio can be calculated; from this ratio, speeds and travel times estimated. However, if $d_{it} < c_{it}$, then this subsection is a bottleneck, and a more elaborate analytical procedure is required.

In this more elaborate case four steps are required. First, since $d_{it} > c_{it}$, then the flow, v_{it}, is equal to c_{it} not d_{it}. Second, since $(d_{it} - c_{it})$ vehicles are being stored upstream of this bottleneck, the previously preducted downstream demands must be reduced. Third, the backward moving shock wave is determined, and new flow and travel time situations upstream of the bottleneck are recalculated. Finally, the excess demand at this bottleneck during this time slice, $d_{it} - c_{it}$, is added to the origin and destination table for the next time slice.

This procedure becomes extremely complicated when several bottlenecks occur and the resulting queues may collide and split at different times and at different locations. Of course, the decreasing queueing situation, which was not described above, is also handled. For more details as to model structure and operations, reference should be made to FREQ3 Model reports[13, 14, 15].

Computer Program

The FREQ3 Model has been computerized, written in FORTRAN IV, and operational on the University of California's CDC 6400 computer and the State of California IBM 360 computer. The computer program consists of the main program which essentially is a "calling" program, 17 subroutines, and one function.

The FORTRAN program deck consists of approximately 2,000 statements. The computer processing time is approximately 4 seconds to run the FREQ3 program on the CDC 6400 computer for a 10-mile congested freeway (30 subsections) and a two and one-half hour period (ten 15-minute time slices), and the computer costs are slightly less than $2.00.

The output from the FREQ3 Model includes speeds, densities, flows, and travel times for each cell; individual trip times and total travel times for each time slice; and total travel distances for the entire study section during the study period.

Model Application

The FREQ3 Model has been applied to a number of different freeway facilities in the United States[16, 17]. Before each site application, a calibration procedure is required to insure that the model results represent the field measured-traffic conditions. The degree of calibration required depends primarily upon the accuracy of capacity and demand input data.

Three quantitative criteria are met before the model is actually used to predict the outcome of operational movement plans. These criteria are:

1. The average trip time for each time slice to travel over the freeway section as computed by the model, is within ± 10 percent of the corresponding field-measured trip time;

2. The total passenger time for the entire freeway section for the total time period as computed by the model, is within ± 2 percent of the corresponding field-measured total passenger time; and

3. All bottlenecks observed in the field are identified by the model, and the beginning time and ending time of congestion at each bottleneck as determined by the model, is within ± 15 minutes of the corresponding field conditions.

The FREQ3 model has then been applied in the investigation of the effect of design modifications, demand changes, ramp control, and priority lanes on improving freeway operations. However, since FREQ3 is a simulation model, it is necessary for the user to generate his own alternatives, and analyze them one-at-a-time. The need for automatically incorporat search procedures was recognized, and has led to decision models which are described in the next chapter.

FREEWAY DECISION MODELS

Three freeway decision models have been developed by extending the FREQ3 Model. The freeway design decision model (hereafter referred to as FREQ3D) includes the FREQ3 model and search procedure for evaluating and selecting design improvement alternatives in a cost-effectiveness framework[18]. The freeway control decision model (hereafter referred to as FREQ3C) includes the FREQ3 Model and a search procedure for determining an optimum ramp control strategy[19]. The freeway priority lane decision model (hereafter referred to as PRIFRE) includes the FREQ3 Model and an evaluation of a preselected set of priority lane strategies[20].

FREQ3D Model

The incorporated search procedure for evaluating and selecting design improvement alternatives includes the five basic steps listed below[18].

1. The FREQ3 Model (which within the FREQ3D Model is actually a submodel) in run for the existing situation.

2. A design improvement alternative is internally generated for each identified bottleneck.

3. The FREQ3 Model is run for each design improvement alternative, and the cost-effectiveness is calculated for each.

4. The most cost-effective design improvement alternative is selected, and the existing situation is modified to include this design improvement.

5. The cost of this improvement is deducted from the budget funds available. If funds still exist, and control is returned to step one above.

This model has been applied to the East Bayshore Freeway in the San Francisco Bay Area. In addition, workshops were held in California and Nevada in which freeway designers were introduced to the FREQ3C Model. The freeway designers were also asked to generate their own alternatives based on their years of experience. An improved cost-effectiveness curve was not identified, and further confidence in this model was developed.

FREQ3C Model

The FREQ3C Model consists of the FREQ3 Model and a linear programming search procedure[19], which together provide the user with three important outputs for each time slice: freeway traffic performance without ramp control, optimum ramp control strategy, and freeway traffic performance with ramp control.

The objective in the linear programming formulation can either be to maximize vehicle-input or to maximize vehicle-miles of travel on the directional freeway.

$$\text{MAX} \sum_{i=1}^{n} X_i \quad \text{or} \quad \text{MAX} \sum_{i=1}^{n} \ell_i X_i$$

where

X_i = desired ramp metering rate

ℓ_i = average trip length

n = number of on-ramps, 1, ..., i, ..., n

The constraints in the linear programming formulation include the following:

$$\sum_{i=1}^{n} A_{ik} X_i \leq B_k \quad \text{for} \quad k = 1, 2, \ldots, m$$

$$X_i \leq D_i \quad \text{for} \quad i = 1, 2, \ldots, n$$

$$X \geq 0 \quad \text{for} \quad i = 1, 2, \ldots, n$$

$$S_i \leq X_i \leq T_i \quad \text{for} \quad i = 1, 2, \ldots, n$$

where

A_{ik} = fraction of traffic from on-ramp i going through subsection k

B_k = the capacity of subsection k

D_i = the demand rate at on-ramp i

S_i = minimum metering rate

T_i = maximum metering rate

m = number of subsections

The FREQ3C Model has been applied to three freeways in the San Francisco Bay Area: East Bayshore Freeway, US 101 - Marin County, and I-280 - San Jose. A series of sensitivity analyses were undertaken to determine the effect of objective function, diversion plan, reserved capacity buffer, minimum and maximum metering rates, weaving capacity, and mainline input fluctuations on the optimum ramp control strategy and the freeway traffic performance under ramp control. Unfortunately, no ramp control strategies have been implemented as a result of the FREQ3C Model, and thus no comparisons can be drawn between model predictions with ramp control and actual field measurements with ramp control.

PRIFRE Model

The PRIFRE Model consists of the FREQ3 Model and an internal procedure for evaluating a preselected set of priority lane strategies[20]. The priority lane strategies are based on the number of lanes (N) allocated to priority vehicles and the minimum vehicle passenger occupancy (P) which is designated as a priority vehicle. The entire $N \times P$ matrix can be analyzed in one computer run with N varying from 1 to the existing number of lanes available minus one, and P varying from 2 or more to 6 or more.

Like the original exclusive bus lane model, three stages (normal operations, priority lane/lanes operations, and nonpriority lane/lanes operation) are analyzed for each cell of the $N \cdot P$ matrix. The measure of effectiveness for all investigations is the change in total passenger time due to the proposed priority lane strategy, and the basic equation is as follows:

$$\Delta TPT = TPTN - (TPTP + TPTNP)$$

where

TPTN = total passenger time for all vehicles under normal operations

TPTP = total passenger time for all priority vehicle passengers in priority lane(s)

TPTNP = total passenger time for all nonpriority vehicle passengers in nonpriority lane(s).

The PRIFRE Model has been applied to US 101 - Marin County in the San Francisco Bay Area, New Jersey Route 3 west of New York City, and to the Lake Front Expressway east of Cleveland. One of the potential benefits of priority treatment strategies is the modal shift of passengers from nonpriority vehicles to the multipassenger vehicles. The model was used in all three site applications to estimate the possible modal shift.

FREEWAY CORRIDOR AND PRIORITY ENTRY MODELS

The two most comprehensive traffic models currently available from ITTE are the Freeway Corridor Model[21] (hereafter referred to as the CORQ1C Model) and the Priority Entry Model[22] (hereafter referred to as the FREQ3CP Model). These models are both decision models and incorporate the FREQ3 Model as a main part of the total model.

Freeway Corridor Model

The CORQ1C Model combines two existing simulation models (FREQ3) and TRANSYT) with an optimization processor[21]. The simulation models are both deterministic and macroscopic, and predict respectively, freeway and street traffic performances as functions of freeway and street designs, allowable ramp and street link flows, and freeway ramp metering and intersection signal settings. The optimization processor is a linear programming model which selects the corridor control settings in coordination with the resulting traffic assignment. Space does not permit a description of this model, and the reader is referred to the earlier CORQ1C Model report[21].

Before applying to the CORQ1C Model to the East Bayshore Freeway Corridor in the San Francisco Bay Area, model results for the existing situation were compared with field measurements, and compared favorably[23,24]. The freeway was nine miles in length and contained nine on-ramps while the surface street system consisted of a major parallel route and all connecting arterials and included 42 signalized intersections.

The model output includes total passenger-hours and total passenger-miles for each part of the corridor for each time slice for existing conditions and for near optimum conditions. In addition, ramp metering rates, ramp queue lengths, and ramp diversion are determined for each ramp and for each time slice.

The CORQ1C Model in its present form should be considered as a first-generation corridor model, and requiring further research.

Priority Entry Model

The FREQ3CP Model is an extension and refinement of the earlier FREQ3C Model[22]. It consists of the FREQ3 Model and an extended linear programming search procedure. As with FREQ3C, the user is provided with three important outputs for each time slice: freeway traffic performance without ramp control, optimum ramp control strategy, and freeway traffic performance with ramp control.

The basic difference between the FREQ3CP Model and the earlier FREQ3C Model is that the objective function has been extended to give the option of also maximizing passenger input or maximizing passenger miles of travel on the directional freeway. Thus the FREQ3CP Model has three modes of operation: (1) as a FREQ3 simulation model with no optimization; (2) as a FREQ3C decision model with optimization and control on a vehicle basis; and (3) as a FREQ3CP decision model with optimization and control on a passenger basis.

A number of other refinements have been added to the FREQ3CP Model such as greater flexibility in modelling traffic diversion schemes and flexibility in pre-selecting any specific ramp control scheme for all particular ramps. Because of these and other refinements, that the FREQ3CP Model should also be used for FREQ3- and FREQ3C-type runs rather than the initially developed models.

The FREQ3CP Model has been applied to three freeways: East Bayshore Freeway in the San Francisco Bay Area, Santa Monica Freeway in Los Angeles, and the Long Island Parkway in New York. First. the FREQ3CP Model was calibrated by comparing the model results with field measurements obtained under existing conditions. Then the model was applied to all three sites and priority entry control strategies determined. The results were most encouraging in terms of user benefits and considering the operational success in Los Angeles, it is expected that this control technique and model application will receive greater attention in the future.

CURRENT RESEARCH

Activities are now underway to further improve the FREQ3CP and TRANSYT Models, to work with local and state organizations in the application of the FREQ3CP and TRANSYT Models, and to sponsore FREQ3CP and CORQ1C workshops. It is anticipated that these activities will be completed sometime during late 1976, at which time further improvements in the CORQ1C Model and conversion of the FREQ3C Model for on-line traffic-responsive ramp control are planned.

Two types of improvement in the FREQ3CP and TRANSYT Models are now underway. First, the measure of effectiveness is being extended to include fuel consumption and air pollution as well as travel times. A performance index which combines these three measures of effectiveness is anticipated. The other improvement is to modify the models so that they are demand-responsive to operational improvements. That is, if a priority entry control strategy is modelled, and there is a significant difference in traffic performance between priority and nonpriority vehicles, the demand pattern for nonpriority vehicles may be modified by considering the spread of the demand over time, the spread of the demand over space, and the spread of the demand to multioccupancy vehicles.

The improved FREQ3CP and TRANSYT Models will be applied to a selected freeway and surface street in the Los Angeles area. University personnel will work with CALTRANS personnel on the freeway application and with City of Los Angeles personnel on the surface street application. The major tasks will be site selection, data collection, model calibration, production runs, sensitivity analysis, and practical interpretation of results. Sharing these tasks with State and City representatives should result in better understanding of the strengths and weaknesses of the models, and the identification of future research needs.

FREQ3CP and CORQ1C Workshops are planned to be held during the coming year in several locations across the country. Each workshop is planned to be approximately of three days duration and will consist of lectures and "on-hands" use of the Models. Detailed course materials will be available including lecture notes and selected model-use type examples. Preparing for these workshops and the interactions with workshop participants should result in better understanding of the strengths and weaknesses of the models, and the identification of future research needs.

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