Abridgment

Integrated Modeling of Freeway Flow and Application to Microcomputers

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An interactive, menu-driven macroscopic freeway simulation program with graphic capabilities is summarized in this paper. In addition to the employment of personal computers, the program has some attractive features that allow simulation at various levels of complexity. Improved macroscopic modeling specifically developed for the program is used to describe complex phenomena, such as lane changing, merging, diverging, and weaving. The freeway is simulated in an integrated fashion; this implies that the coupling effects of ramps are considered in determining actual entering and exiting flows as well as in following the simultaneous development of queues and propagation of congestion on both the freeway and its ramps. Input to the program is entered interactively and includes conventional traffic parameters, freeway and ramp characteristics (e.g., capacity, free flow speed, jam density), demands (including percentage of exiting volumes at off ramps), and geometric information. Output includes estimation of delays, stops, energy consumption, pollution levels, and other important measures of effectiveness. In addition, two- and three-dimensional plots of speed flow and density are produced for dynamic description of these basic variables in time and space; additional graphics include visual review of the freeway operation during the simulation as well as description of the geometrics, demand patterns, and other input information.

Detailed and realistic analysis of freeway flow dynamics, even in simple situations, can rarely be made analytically or with other convenient tools such as nomographs or design curves. Such analysis is needed in comparing alternative geometric configurations, estimating the effects of improvements, determining the adequacy of traffic management schemes, assessing the impact of control strategies, studying the formation and dissipation of congestion on the freeway and its ramps, and so forth. Although analytical and empirical approximations for answering problems such as these could be made, at best only crude estimates can be expected. More accurate results are usually obtained through simulation. However, this option implies accessibility to software and large computers that are not always readily available to practicing engineers. Furthermore, complexities of software, hardware, or both, make employment of simulation unattractive to the average user.

To make employment of simulation appealing and easily accessible, an interactive, menu-driven microcomputer-based freeway simulation program called KRONOS was recently developed *(1)*. In addition to the employment of personal computers, the attractiveness of the program lies in three areas: (a) its simplicity both in terms of entering the input and interpreting the output, (b) its flexibility in terms of desired accuracy and selecting modeling complexity, and (c) its completeness in terms of graphic capabilities and estimation of the measures of effectiveness. Despite these advantages, the program to this point was available only in a prototype form, that is, it was largely untested and had limitations that are typical of similar experimental software. Since the inception of its initial version, substantial modeling and programming modifications and enhancements have been made. Such improvements include modeling of the freeway and its ramps in an integrated fashion, increased program capabilities, estimation of additional measures of effectiveness, and reduction of memory requirements and execution times. Most importantly, testing against real and simulated data was performed and adjustments were made accordingly.

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A major advantage of the program is that it takes into account important traffic phenomena not previously considered by earlier macroscopic programs. Such phenomena include lane changing, merging, diverging, weaving, spillbalk, and friction effects. This was made possible through extensive macroscopic model development and experimentation. In this modeling, the coupling effects of ramps are considered in determining actual entering and exiting flows as well as in following the simultaneous development of queues and propagation of congestion on both the freeway and its ramps.

In the following sections, a brief discussion of the program's modeling and analysis methodology is presented along with its capabilities; more details can be found elsewhere *(2–4)*.

MODELING METHODOLOGY

As mentioned, a number of modeling adjustments were made after testing the initial version of the program with actual and simulated data. Space limitations do not allow detailed model description; this is presented elsewhere *(1–4)*. Suffice it to say that KRONOS IV employs simple continuum models that assume an equilibrium speed-density (or flow-density) relationship. Employment of high-order continuum models, initially allowed in KRONOS I, did not prove to be more effective at least in moderate to heavy flows and were therefore eliminated in subsequent versions. Model implementation is made by discretizing the time space domain in short increments, t and x, respectively, such that $\Delta x/\Delta t > u_f$, where u_f is the free flow speed. Space discretization of a section that includes the most typical freeway components is shown in Figure 1. It should be stressed that this discretization is only mathematical (i.e., it is only done for computational purposes) and not physical.

Although distinct boundaries exist between the freeway components, flow at these boundaries is determined during the

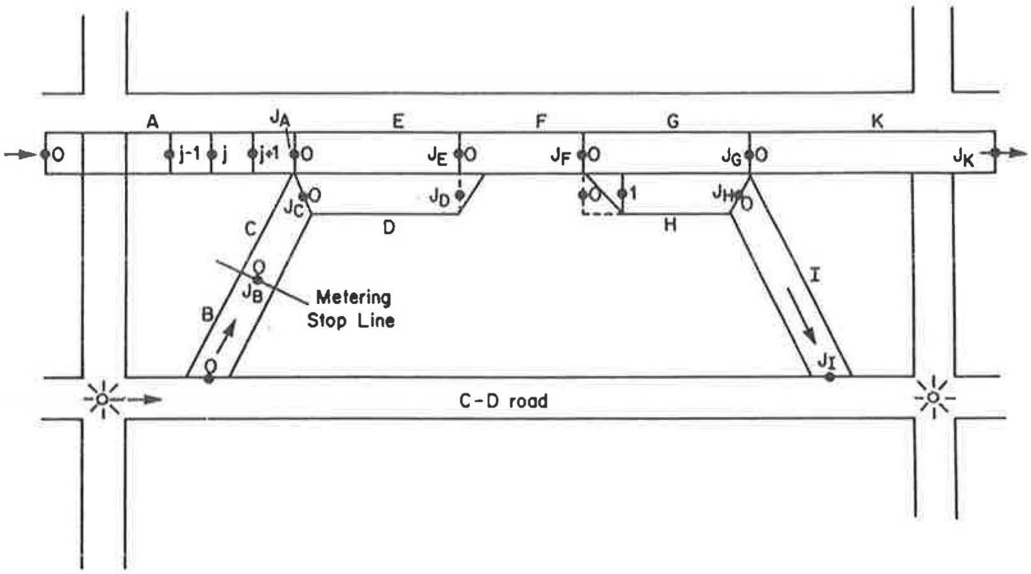

FIGURE 1 **Space discretization of a freeway section.**

solution of the state equations. The only exception is at external boundaries (such as the upstream and downstream ends of the freeway, and the junctions of ramps with the adjacent surface streets) or certain internal ones (such as the metering stop lines and the beginning or ending nodes of deceleration and acceleration lanes, respectively). Flow at these boundaries is specified from the arrival and departure patterns, the metering rates, or other physical considerations.

PROGRAM SUMMARY

The KRONOS IV program employs the previously summarized modeling for dynamically calculating k, u, and Q on each node and segment x. From these basic flow parameters, total travel *(TT)*, total travel time *(TTT)* delay, the duration and extent of congestion (including queue length and size), and energy consumption and pollution levels are derived. These results are summarized by zone (defined as a section between ramps or a merging diverging or weaving area) and by ramp. In ramps the number of vehicles entering and leaving as well as the average and maximum queue length and size are also presented. Both intermediate and final results of the measures of effectiveness are produced. Two and three dimensional plots of k, u, and Q are also produced in order to show the dynamic changes of these variables in space and therefore visualizing the propagation and dissipation of shock waves and congestion on both the freeway and its ramps. For a quicker and easier presentation of the propagation of disturbances along the highway as well as for an easy review of its operation (perhaps after an improvement), the discretized form of the freeway is presented on the graphics screen and each segment is repainted continuously (from blue to red) according to its density as the simulation proceeds.

Additional graphic capabilities of the program are related to the interactive preparation of the input in a fashion requiring minimal reference to the manual. For instance, the geometrics are entered by segmentation and selection of the configuration of each segment from a number of alternatives presented on the graphics screen. Following definition of the geometrics for each segment, the entire freeway is shown for verification.

The remaining input requirements are entered interactively through a series of questions and options as currently done in most expert systems. These inputs are related to the freeway and ramp demand patterns, traffic composition, exiting volumes upstream of entrance ramps, and departure patterns at exit points (off ramps and the downstream end of the freeway). Arrival and departure patterns are also plotted for verification, and can be as complex as desired. The program allows employment of user-specified speed flow models, which are also entered interactively; a default model can be used as an alternative. The u–k model determines capacity of each freeway zone; ramp merging capacity is not needed because the actual number of automobiles entering the freeway is determined during the simulation. Changes to input already entered can be made at any stage during the data entry, and future modifications of a coded facility can easily be accomplished by entering the desired changes only. Finally, input to the program can be short or extended, depending on the accuracy desired. In experimental runs, the time required to enter the necessary data for simulating a three-lane section that is 2 mi long with two ramps for 1 hr using 5-min time varying demands ranged from 10 to 25 min, depending on the user's familiarity with the program.

CAPABILITIES, HARDWARE, AND SOFTWARE REQUIREMENTS

Currently the program can simulate a freeway section up to six lanes wide and approximately 10 miles long. The section can contain up to 20 entrance and 20 exit ramps, while auxiliary lanes between ramps are allowed. A complete list of the program's capabilities includes the following:

1. Reported after each time slice, $N\Delta t$:
   a. Total travel,
   b. Total travel time,

c. Delay,
d. Total arrivals and departures,
e. Queue size and length on each ramp,
f. Energy consumption, and
g. Pollution levels.

2. Reported after simulation is complete:
   a. Plot of speed, flow, or density as a function of distance, time, or both, either two-dimensionally or three-dimensionally;
   b. Plot of congestion areas as a function of time;
   c. Summary of total arrivals and departures;
   d. Number of vehicles in the system at the end of simulation; and
   e. A summary of the measures of effectiveness listed in 1.

3. Color graphics display of density as a function of distance during program execution.

4. Hard copies of all plots (including geometrics) can be obtained through the printer while the input summary and the results of calculations are routed either to the monitor or the printer.

In its current form, the program requires an IBM personal computer with a minimum of 320 K of memory, keyboard, and two floppy disk drives with a minimum storage capacity of 320 K bytes each. It also requires a monochrome monitor, an adaptor, an 80-column printer with graphic capabilities, and a color monitor and color display adaptor. The only software required is the PC-DOS or MS-DOS operating system version 1.1 or higher. Simulation time can be substantially reduced if an IBM-PC 8087 math co-processor board is added to the system. Because the program is available in compiled form, only the software just mentioned is needed. Recompilation of the source code requires the MicroSoft Pascal compiler version 3.2 and access to a disk drive with at least 400 K bytes of disk storage. It is estimated that the total cost for obtaining the hardware just mentioned including options is less than $4,000.

TESTING AND VALIDATION

The early versions of the program were implemented to a number of exemplary situations that covered the entire range of speed flow and density domain and included both entrance and exit ramps as well as multiple lanes. Subsequently, the results were compared with those obtained from microscopic simulation using INTRAS, a recently developed and calibrated program *(5)*. Microscopic simulation during the initial development stage was justified by the need to allow demands and generation rates to fluctuate sufficiently in a controlled environment at relatively short time intervals. A second reason for microscopic data-base generation was the need to impose tractable initial and boundary conditions in order to allow intuitive inspection of the results. The objective of the initial testing was to determine the most appropriate continuum model (among three simple and high-order alternatives) and best numerical algorithm (among a number of options) for use by subsequent versions of the program. In addition, it was necessary to test and adjust the modeling of multilane, merging diverging, and weaving dynamics.

Although the results of the initial tests were encouraging and allowed adjustment of several model parameters, testing with real data was also performed. Such tests required detailed calculations and measurement of k, u, and Q at short time and space increments as well as estimation of the measures of effectiveness at the end of the test period.

Cost considerations did not allow extensive field data collection and analysis; thus, alternative data sources were sought. After requests were made to several sources, the FHWA, U.S. Department of Transportation, provided the most detailed data that could be found at the time of the testing. These data were collected in a recent project at a number of locations around the United States and are microscopic in nature, that is, they include the time individual vehicles cross speed traps placed at strategic locations along selected sections of the freeway *(6)*. Because of the study limitations, the number of test locations was restricted to four, representing typical freeway components, namely, pipeline, merging, diverging, and weaving sections *(4)*.

Comparisons with the field data led to similar conclusions with the simulated data base. Interestingly, it was found that discontinuous equilibrium u–k models generally increased accuracy, and this was more pronounced in the diverging case. However, because derivation of such relationship is rather tedious for most practical applications, a generalized one was derived from the available data in all sites. To demonstrate that the program can realistically handle larger freeways, a real freeway section approximately 10 miles long, containing 19 ramps and 3 basic lanes, was simulated for 90 min; the results favorably compared with earlier data *(4)*.

CLOSING REMARKS

The most interesting feature of the KRONOS IV program is its ability to run on a microcomputer while its results are in agreement with both real and simulated data. This was made possible by the simplicity of the modeling and numerical methodologies developed, which allow quick and accurate calculation of the basic flow variables in both time and space. Incidentally, it is worth mentioning that three-dimensional models that explicitly take street width into account (along with time and length) were also developed *(2)*, but were later excluded for reducing the computational effort. Based on discussions and comments received to this point, the authors feel compelled to repeat that the proposed discretization is only mathematical, not physical; this implies that both data and field measurements should only be made in larger sections (zones), as in most practical applications. Of equal importance is the integrated treatment of ramps, acceleration and deceleration lanes, merging and diverging, and weaving areas, as well as the inclusion of lane-changing effects. This is a feature that along with the interactive graphics has been missing from earlier macroscopic programs.

Despite the program's advantages, which should encourage employment of simulation by practicing engineers, certain shortcomings should be recognized. The most important one is related to execution time, which can be very long as the size and complexity of the freeway increases. For instance, execution time for a three-lane, two-ramp section for 1 hr, including detailed lane-by-lane analysis and all graphic options, is approximately 18 to 19 hr, which can be considered long compared with the much faster performance of large computers.

However, recent hardware advances (such as the introduction of the IBM-PC/AT) as well as new software development (such as the new Turbo-Pascal) should reduce execution time considerably. Additional enhancements that should make the program more attractive are possible and some are planned. Such improvements are related to inclusion of left-hand-side ramps, collector distributor roads, incidents, high-occupancy-vehicle–priority treatment, demand diversion, generation of origin-destination patterns after implementation of a new management policy, estimation of optimal ramp metering lanes, and so forth. Such improvements will allow treatment of most freeway operational problems one is likely to encounter in practice.

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