Dynamic Freeway Simulation Program for Personal Computers

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ABSTRACT

An interactive menu-driven macroscopic freeway simulation program with graphic capabilities is presented. The program is written in UCSD-Pascal language and runs on IBM personal computers. Recently developed flow models that describe complex phenomena such as lane changing, merging, and weaving are employed. The computational effort is minimized by using fast and efficient numerical methods for implementing these models. Input to the program is conventional traffic parameters, freeway and ramp characteristics (e.g., capacity, free-flow speed, jam density), demands, and origin-destination information. Output includes dynamic description of speed, flow, and density (both numerical and graphic); estimation of the most common measures of effectiveness; and graphic representation of flow conditions and congestion levels.

Improving the operating conditions of freeway flow during periods of congestion is one of the major problems in traffic engineering practice. Before implementation of an improvement, estimation of the effects of the various alternatives and comparison with the existing conditions are desirable. This usually entails determination of the measures of effectiveness (such as total travel, total travel time, delays, stops, energy consumption, and so forth) associated with a given situation, which may include a traffic management scheme. Often, a more detailed analysis is needed, which may require dynamic description of flow (i.e., in time and space) as well as the formation and dissipation of congestion. Such analysis could assist in comparing alternative geometric configurations; estimating the effects of incidents; and, in general, assessing the impacts of improvements, control strategies, and system changes. Finally, it may be necessary to determine only whether a given facility and management scheme combination can accommodate the demand in a satisfactory fashion.

Despite recent theoretical developments, simple tools for analyzing situations such as these are still lacking. Because analytical methods for describing the freeway flow process in sufficient detail and accuracy are impractical, field engineers often must turn to simulation to obtain answers to the previously mentioned problems. A number of freeway simulation programs are available for design and analysis purposes; among the most widely known programs are FREQ6PE (1), FREQ7PE (2), and INTRAS (3). The first two are very similar and are macroscopic in nature; the latter is microscopic. At present, existing program packages can run only on large computers that are not always easily accessible; furthermore, using a large computer usually implies familiarity with its operating system for compiling the programs for tape, disk, input-output (I/O) operations, and so forth. Finally, existing programs are cumbersome and data hungry, and they require reasonable familiarity with the program.

Difficulties of this nature make existing packages unattractive to potential users. Previous experience (4) suggests that the use of large-scale freeway simulation packages in at least one agency was essentially abandoned shortly after an initial trial period. Some of the difficulties related to the use of large computers can be resolved by recent advances in microcomputer technology. The low cost and anticipated widespread use of personal computers combined with the opportunity of employing less sophisticated menu-driven, user-friendly interactive programming make development of microcomputer software increasingly attractive and desirable.

In this paper an interactive, user-friendly macroscopic simulation program named KRONOS-1 is presented; the program is written in UCSD-Pascal language and runs on IBM personal computers. Because of the limitations of microcomputers, the models employed had to require minimal storage and computational effort and be fairly realistic and reasonably accurate. The last two requirements were satisfied by taking compressibility into account, as well as acceleration and deceleration characteristics of a traffic mass. Storage and computational effort were reduced by developing simple finite-difference schemes for solving the governing equations of the system. To further improve realism, merging or diverging areas are not treated as dimensionless points (as in most of the existing programs), but they have a finite length. The generation (or dissipation) of flow in these areas is a function of the relative speed between the freeway and the acceleration (or deceleration) lane, as well as the ramp demands (or exiting volumes) and freeway flow conditions in the merging (or diverging) area.

Perhaps the major advantage of the program presented here is that it allows treatment of phenomena not previously described by existing macroscopic programs. Such phenomena include lane changing, merging or diverging, and weaving. This was made possible through earlier extensive model development and experimentation. Testing and validation were performed by comparing the results of the program with a data base generated by microscopic simulation using the INTRAS program (3). This was necessitated by the need to test a wide range of ramp and freeway demand combinations as well as a number of alternative geometric configurations. Stated otherwise, cost and time considerations dictated experimentation under a controlled environment that was ensured by a previously tested and validated microscopic simulation program. It should be noted, however, that more extensive testing against field data, as well as program extensions, is under way.

MODELING AND ANALYSIS METHODOLOGY

Because of the limitations of personal computers, bookkeeping and storage requirements, as well as computational effort, should be minimized. This led to the selection of macroscopic flow models for the KRONOS-1 simulation program. Previous experience (4,5) suggests that macroscopic simulation can lead to satisfactory accuracy at least for some of the problems described earlier. Existing macroscopic flow models fall into three general categories: (a) input-output (I/O), (b) simple continuum, and (c) high-order continuum. The models of the first category are rather simplistic in that they do not include space explicitly nor do they take compressibility into account. High-order continuum models, on the other hand, are the most sophisticated but they have not as yet gained wide popularity or proved truly superior to the simple-continuum alternative. In a recent study (6) these models performed about the same as the simple-continuum alternative. For this reason, the main model employed by KRONOS-1 is the simple-continuum one, presented here, which is based on the conservation equation. It should be noted, however, that the program also allows use of the most widely known high-order model (7).

According to the simple-continuum model (8), freeway flow can be described by the conservation equation that has the general form:

$$(\partial q/\partial x) + (\partial k/\partial t) = g\ (x,t) \tag{1}$$

where

$q = q(k) = ku$ is the flow rate of the traffic stream;
$k = K(x,t)$ and $u = u(k)$ are the density and speed, respectively;
t and x = time and space; and
g = the generation rate.

The latter represents generation or dissipation of cars at entrance or exit ramps, respectively. Therefore, g as well as the basic flow variables (k, q, and u) vary with time and space. Naturally, in freeway sections where there are no entrances and exits $g(x,t) = 0$. The continuum model assumes that flow is a function of density; this implies that Equation 1 is a nonlinear (i.e., hyperbolic) partial differential equation having density as the only unknown. It follows that this equation can be solved for a particular freeway to obtain the value of density (and therefore flow and speed) at each time and space point of the t-x domain. Analytical solution of this problem (i.e., estimation of k, q, and u in time and space) is only possible for continuous single-regime q-k relationships, simple arrival and departure patterns at the boundaries of the freeway in question (boundary conditions), zero generation terms, and simple flow patterns along the road at the beginning of simulation (initial conditions).

To circumvent the mathematical complexities of analytical solutions, to improve realism (by relaxing simplifying assumptions), and to allow further practical extensions, numerical treatment of Equation 1 (governing equation) was sought. The numerical solution of Equation 1 begins by discretization in both time and space. Figure 1 shows space discretization of a freeway section that consists of J segments of length Δx. It can be easily verified that, to keep the solution within reasonable bounds, the time and space increments Δt, Δx must obey the rule:

$$(\Delta x/\Delta t) > u_f$$

where u_f represents the free flow speed. Numerical solution of the conservation equation requires knowledge of the arrival and departure patterns (boundary conditions) at each end of the freeway section under consideration (nodes 1 and J+1 in Figure 1). When numerical methods are employed, no specific assumptions need to be made concerning these patterns (i.e., either deterministic or statistical arrival and departure distributions can be assumed).

Dynamic estimation of density, flow, and speed (i.e., estimation of these values on every node j at each Δt increment) is obtained from (6):

$$k_j^{n+1} = [(1/2)(k_{j+1}^n + k_{j-1}^n)] - [(\Delta t/2\Delta x)(G_{j+1}^n - G_{j-1}^n)] + (\Delta t/2)(g_{j+1}^n + g_{j-1}^n) \qquad \forall_j \tag{2}$$

$$u_j^{n+1} = u_e\,(k_j^{n+1}) \tag{3}$$

$$q_j^{n+1} = k_j^{n+1}\, u_j^{n+1} \tag{4}$$

where

k_j^n, u_j^n, q_j^n = density, speed, or flow, respectivity, of node j at $t = t_o + n\Delta t$,
t_o = initial time,
$u_e(k_j^{n+1})$ = equilibrium speed corresponding to the value of density k_j^{n+1},
$G_j^n = K_j^n u_j^n$, and
$g_j^n = g(x_j, t_n)$ = generation rate of node j at $t = t_o + n\Delta t$.

When the simplest equilibrium speed density model is assumed (9),

$$u_e\,(k_j^{n+1}) = u_f\ [1 - (k_j^{n+1}/k_o)] \tag{5}$$

and

$$G_j^n = k_j u_f\ [1 - (k_j^n/k_o)] \tag{6}$$

where k_o and u_f represent jam density and free flow speed, respectively.

This numerical solution allows use of any speed-density model, including discontinuous ones; in such case, Equations 5 and 6 can be altered accordingly. It should be noted that the generation rate g is either given or it can be derived dynamically from ramp demands and freeway flow and density at the previous time step. In the simplest case, where the entire ramp equals the segment length Δx, an average value of g can be assumed; however, as the ramp length increases or as Δx decreases, this assumption is unrealistic. In such a case, solution proceeds by considering the conservation equation of the acceleration lane separately and solving it simultaneously with the conservation equation of the freeway (10). This new equation must take into account lane changing effects that are described next.

The modeling presented to this point does not consider lane changing effects (i.e., all lanes are aggregated). Lane changing can be described in two ways (10); the first, and simplest, is discrete in the sense that it considers each lane separately. The second is continuous (i.e., it explicitly includes street width). Because of space limitations only the first option is described here.

A simple-continuum model for describing flow along two or more homodirectional lanes can be obtained by considering the conservation equation of each lane. This is accomplished by observing that the exchange of flow between lanes represents gener-

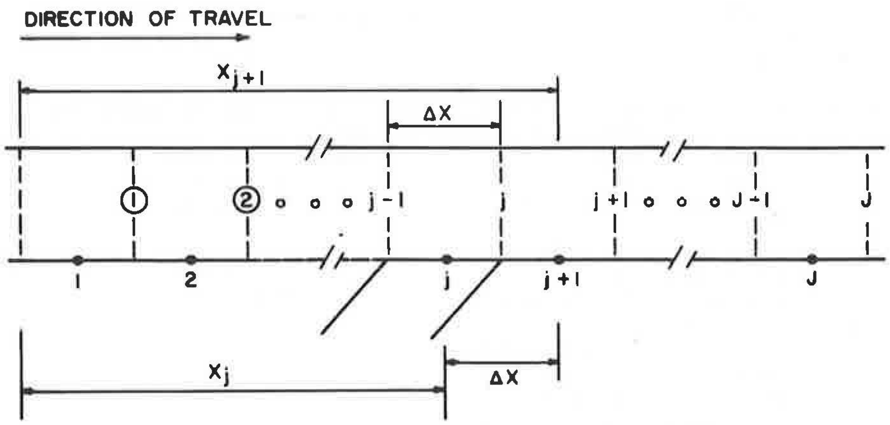

FIGURE 1 Space discretization of a freeway section.

ation (or loss) of cars in the lane under consideration. Following Gazis et al. (11), Munjal and Pipes (12), and Michalopoulos et al. (10), the simple-continuum system of equations describing flow on a two-lane freeway is

$$(\delta q_1/\delta x) + (\delta k_1/\delta t) = g + Q_1 \qquad (7)$$

$$(\delta q_2/\delta x) + (\delta k_2/\delta t) = Q_2 \qquad (8)$$

where

- t, x = time and space coordinates, respectively
- $q_i(x,t)$ = flow rate of the ith lane (i=1,2)
- $k_i(x,t)$ = density of the ith lane (i=1,2)
- $Q_i(x,t)$ = lane changing rate (i=1,2)
- $g(x,t)$: generation rate of lane 1; at exit ramps g is negative

$$Q_1 = \alpha\{[k_2(x,t-\tau) - k_1(x,t-\tau)] - (k_{20} - k_{10})\} \qquad (9)$$

$$Q_2 = \alpha\{[k_1(x,t-\tau) - k_2(x,t-\tau)] - (k_{10} - k_{20})\} \qquad (10)$$

α = a sensitivity coefficient describing the intensity of interaction between lanes. In the simplest case α can be assumed constant; alternatively (10):

$$\alpha = \begin{cases} 0 & |k_2(x,t-\tau) - k_1(x,t-\tau)| \leq k_A \\ [\alpha_{max}/(k_o - k_A)]\,[|k_2(x,t-\tau) - k_1(x,t-\tau)| - k_A] & |k_2(x,t-\tau) - k_1(x,t-\tau)| > k_A \end{cases} \qquad (11)$$

- k_A = a constant value below which no exchange of flow occurs
- τ = an interaction time lag (a value of zero could be assumed for simplicity)
- k_{io} = an equilibrium density value that, if exceeded, will result in lane changing; i=1,2
- k_o = jam density
- g = generation term in lane 1 due to merging or diverging; this term also appears in Equation 1.

As before, the system of governing equations (Equations 7 and 8) can be solved numerically by discretizing in time and space. Figure 2 presents space discretization of a two-lane freeway section that includes an entrance ramp. It should be noted that for estimating average q, k, and u of any segment j, the nodes in Figure 2 are placed in the middle of each segment. This slight modification can also be made when all lanes are aggregated. The numerical solution allowing estimation of k, u, and q at each node and time increment is (10)

$$k^{n+1}_{1,j} = [(1/2)(k^n_{1,j+1} + k^n_{1,j-1})] - [(\Delta t/2\Delta x)(G^n_{1,j+1} - G^n_{1,j-1})] + [(\Delta t/2)(g^n_{j+1} + g^n_{j-1})] + (\Delta t/2)(Q^n_{1,j+1} + Q^n_{1,j-1}) \qquad (12)$$

$$k^{n+1}_{2,j} = [(1/2)(k^n_{2,j+1} + k^n_{2,j-1})] - [(\Delta t/2\Delta x)(G^n_{2,j+1} - G^n_{2,j-1})] + [(\Delta t/2)(Q^n_{2,j+1} + Q^n_{2,j-1})] \qquad (13)$$

where

- $k^n_{i,j}$: density of the ith lane in the jth segment at $t = n \cdot \Delta t$ (i = 1,2)
- $Q^n_{1,j} = \alpha^{n-s}_{1,j}\,[(k^{n-s}_{2,j} - k^{n-s}_{1,j}) - (k_{20} - k_{10})]$
- $Q^n_{2,j} = \alpha^{n-s}_{2,j}\,[(k^{n-s}_{1,j} - k^{n-s}_{2,j}) - (k_{10} - k_{20})]$
- $s \cdot \Delta t$ = interaction time lag (=τ)
- $\alpha^{n-s}_{i,j} = f(k^{n-s}_{1,j} - k^{n-s}_{2,j})$ as suggested by Equation 11; $\alpha^{n-s}_{i,j}$ could also be assumed constant
- $G^n_{i,j} = k^n_{i,j} \cdot u^n_{i,j} = k^n_{i,j} \cdot u_e(k^n_{i,j})$ (i = 1,2)
- $u_e(k^n_{i,j})$ = equilibrium speed corresponding to $k^n_{i,j}$; assuming the simple equilibrium model of Greenshields (9), it can be easily verified that $G^n_{i,j} = k^n_{i,j} \cdot u_f[1 - (k^n_{i,j}/k_o)]$ where u_f and k_o represent the free flow speed and jam density, respectively. However, more realistic u-k models are recommended.

Following computation of density at each time step the flow rate $q^{n+1}_{i,j}$ and speed $u^n_{i,j}$ are obtained from

$$u^{n+1}_{i,j} = u_e(k^{n+1}_{i,j})$$

and

$$q^{n+1}_{i,j} = k^{n+1}_{i,j}\,u^{n+1}_{i,j}$$

Extension of the simple-continuum model to more than two lanes is straightforward. Generalization to any number of lanes and further details concerning

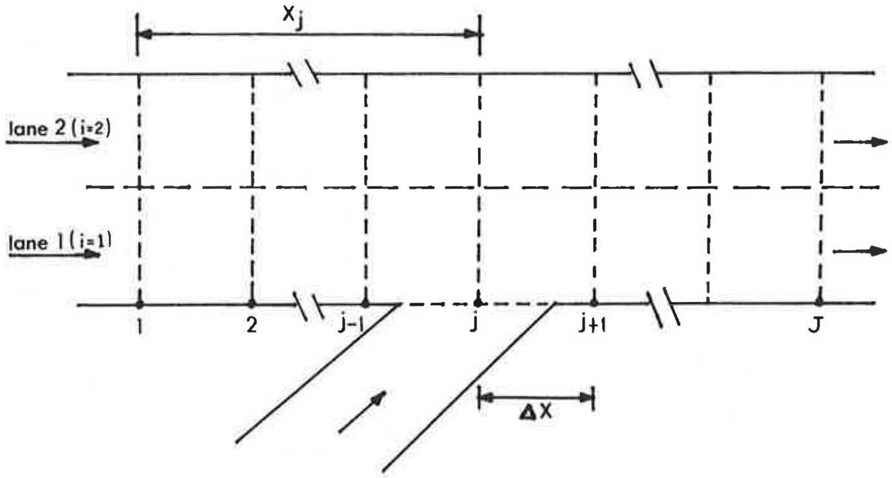

FIGURE 2 Space discretization of a two-lane freeway section.

the treatment of long merging and diverging areas, as well as weaving, are incorporated in KRONOS-1. Before concluding this section, it should be mentioned that a similar formulation and solution of the multilane problem can be extended to high-order models such as those proposed by Payne (7) and Phillips (13). Finally, it should be evident that when speed, flow, and density are known at every x and t, calculation of total travel (TT), total travel time (TTT), delays, stops, and energy consumption can easily follow.

GENERAL PROGRAM CAPABILITIES

The KRONOS-1 simulation program employs the previously summarized modeling for calculating speed flow and density dynamically on every node lying in the middle of each segment Δx. Delay is calculated from the difference between the travel times obtained from the actual speed and a user-specified minimum speed u_{min}; that is, cars are assumed to be delayed if they travel at a speed lower than u_{min}. Average values of q, k, u, total travel (TT), total travel time (TTT), and delay are found by zone (defined later in this section) or for the entire facility. At the end of simulation the program provides a summary of the number of cars arriving and departing each boundary of the freeway, as well as the ramps, the number of cars remaining on the freeway, and the queue length and size on the ramps at that time. Average and maximum values of the last two state variables are also calculated. Finally, the program produces a number of plots showing the change of q, k, and u in time and space, and the formation and dissipation of congestion, either by lane or in an aggregate fashion. Extensions are currently being made for calculating energy consumption and pollution levels.

In its present form, KRONOS-1 allows employment of user-specified speed-flow models (including discontinuous ones); alternatively, a default model can be employed. Further, arrival patterns can be constant or time dependent, deterministic or stochastic. Parameters of the selected 4-K model can also be specified by the user, and the flow model employed can be the simple or high-order continuum or a combination of the two (hybrid model). The user has the option of using a short input version; further, the results can be aggregated over all lanes or they can be presented in a lane-specific fashion. Finally, the merging, diverging, and weaving patterns can either be specified by the user or determined dynamically as a function of freeway volumes, capacity, geometrics, and ramp demands.

INPUT REQUIREMENTS

Because of the macroscopic nature of the program and the simplicity of the model, input requirements were kept to a minimum. Input is generally entered interactively in seven stages; alternatively, input could be retrieved from a disk file. Depending on the amount of detail desired, a reduced or an extended input version can be selected. The former employs a predetermined set of values for the model parameters; in the extended input version these parameters can be user specified as described in this section. From experience gained to this point it was found that input for the extended version can be entered in about 5-10 minutes per freeway mile, depending on the complexity of the situation, and the short version can save 25 to 50 percent of this time.

The first set of information required by the program includes the geometrics of the facility under consideration. The geometrics are found by dividing the facility into zones as shown in the lower part of Figure 3. The length and number of lanes in each zone must be specified as well as the length of each ramp.

Following the geometric input, the program requests the user to enter the freeway characteristics. These include a speed-density model that can be entered in numerical form (i.e., pairs of values of k and u) for each zone or it can be the same for the entire freeway. This model can be discontinuous. Alternatively, Greenshield's (9) model can be used as a default option. In addition to the u-k relationship, freeway characteristics include the free flow speed, the minimum speed for estimating delays, the jam density, and the capacity of each zone and ramp. It should be noted that ramp capacity should be given in terms of saturation flow, which depends on the geometrics of the ramp. The actual number of cars entering or leaving the ramps is determined (dynamically) by the program according to the user-specified arrival and merging patterns and the freeway flow conditions.

The third set of input data contains information related to simulation parameters; that is, it includes the simulation time, the initialization period, the time increment Δt, and the segment length Δx. The latter can be uniform for the entire freeway or it can vary in each zone.

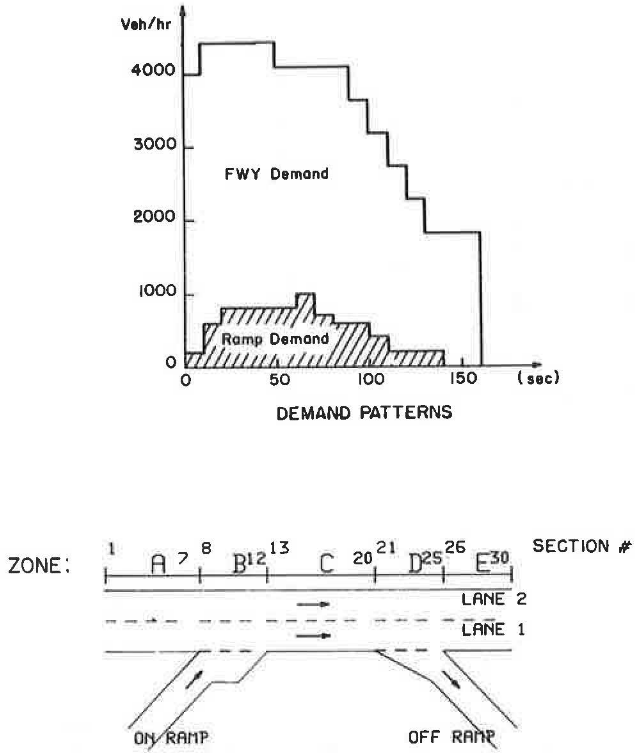

FIGURE 3 Demand patterns and division of freeway in zones.

Next, the program requests the initial conditions (i.e., the q, or k, or u distribution along the facility at t=0), which can be variable or uniform. An empty freeway can be selected as a default option.

The fifth input set is related to the arrival and departure patterns. These include the upstream end of the freeway and the ramps. Arrivals on the freeway and ON ramps can be constant, time varying as specified by the user or stochastic. In the latter case, the user must specify the mean and the variance of the arrivals. With respect to the departure patterns at the downstream end, it is assumed that there is no congestion so that $k^n_{J+1} = k^n_J$; alternatively, the departure pattern can be user specified. The percentage of cars exiting at the OFF ramps must be specified. In Figure 3 this refers to the percentage of cars in zones exiting at the OFF ramp. This percentage could be constant or time varying and is related to the origin-destination patterns. The latter are also needed in weaving sections.

Following definition of the boundary conditions the user must specify the particular model to be used as well as the merging pattern that best fits the ramp under consideration. This pattern is a function of ramp demands and freeway flow conditions and can be uniformly distributed along the acceleration lane; alternatively, it can be linearly or exponentially decreasing with distance. Finally, as a default option, the program can determine the merging pattern dynamically based on the freeway and ramp flow conditions as well as the ramp demands.

Next, the program asks the user to select the particular traffic model to be employed in the simulation. As mentioned earlier, either the simple or the high-order models can be used; in addition, KRONOS-1 allows use of a third hybrid model that is a combination of the two (6). The final set of input is related to the type and format of the output desired. This includes the type and frequency of the 2-D and 3-D plots desired, averaging of the results over a user-specified time increment, the unit where output is to be displayed (i.e., CRT, printer, plotter, graphics screen), whether hard copies of both input and output are desired, and so forth.

In the short input version of the program it is assumed that (a) Δx = 100 ft, (b) Δt = 1 sec, (c) the road is empty at t = 0, (d) the simple continuum model is employed, and (e) the merging pattern is determined by the program. Therefore, the user must enter only the simulation time, the geometrics and freeway characteristics, the arrival flow patterns, the percentage of volumes exiting, and the type of output desired. Following completion of the input, the program checks for errors and gives the user the opportunity to make changes or store the input data in a disk file for further modifications in a later run. Input information such as the geometrics and demand patterns is also plotted for quick visual inspection. The upper part of Figure 3 shows the demand pattern used for the typical entrance and exit ramp configuration shown in the lower part of the figure. The numbers adjacent to the zones represent the segments assigned to the boundaries of each zone.

PROGRAM OUTPUT

The program is executed in a time-scan fashion; that is, time is advanced by Δt and from the boundary conditions, and the solutions at $t-\Delta t$, k, u, and q are computed in the middle of each segment Δx; similar computations are made for the ramps, including the acceleration lanes. Subsequently TT, TTT, delay total arrivals and departures are updated, as well as queue size and queue length on each ramp along with the remaining statistics of the system (total and average stops, average q, k, and u by zone, and so forth). As time elapses, u, k, or q is plotted as a function of distance every $N\Delta t$ seconds where N is specified by the user. Inspection of these plots assists in visualizing the formation and dissipation of congestion, as well as the evolution of queues in x and t. Figure 4 shows the density distribution per lane in space at t = 100 sec for the situation shown in Figure 3. The value of density is also printed; the symbol + indicates that density in both lanes 1 and 2 is about the same for a particular segment; symbols r, m, and v represent density at the ramp proper and the acceleration and deceleration lanes, respectively.

In addition to the detailed plots, 3-D plots of similar nature are produced. Such a plot, representing density on each lane as a function of x and t, is shown in Figure 5. This figure can be used for general inspection of the results, and further details can be found in Figure 4. As mentioned earlier, plots similar to those of Figures 4 and 5 can also be generated for flow and speed.

During the simulation, density of every segment is compared with a threshold value representing capacity; if this value is exceeded, the segment is assumed to be congested, and at the end of simulation a plot is produced showing congestion as a function of time and space. Such a plot for the situation of Figure 3 is shown in Figure 6, which depicts the duration and extent of congestion in lane 1. A better visualization of the formation and dissipation of congestion in time and space, as well as of the dynamic change of density along the road, can be seen on the graphics screen that depicts in color the value of density along the road. Because the screen is repainted every Δt, a very vivid representation of the flow dynamics and the evolution of congestion is realized.

At the end of simulation a summary table is produced showing the average value of q, k, and u for

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Time= 100.0   (Step=100)   DENSITY
SEC.                    0        50        100       150       200(Veh/Mil)
  #  lane#1  lane#2 ramp+----+----+----+----+----+----+----+----+----+--
  1    54.0    52.4     :         21
  2    59.4    54.9     :          21
  3    68.4    59.2 12.9:  r        2 1
  4    78.2    63.2 12.9:  r         2  1
  5    90.5    69.1 12.9:  r          2   1
  6   100.3    73.4 12.8:  r           2    1
  7   109.3    78.4 12.3: r             2     1
  8   115.1    81.6  9.9: m             2      1
  9   117.0    84.6  7.6: m              2     1
 10   115.4    86.3  5.5:m               2     1
 11   112.6    87.4  3.3:m               2     1
 12   107.7    87.7  2.4m                 2   1
 13   101.5    87.5     :                 2 1
 14    96.6    86.9     :                2 1
 15    92.3    85.9     :                21
 16    88.3    84.7     :                21
 17    84.3    83.3     :                +
 18    79.8    81.7     :               +
 19    74.4    80.0     :              12
 20    67.3    78.1     :            1  2
 21    56.1    76.2  6.4:v         1   2
 22    49.0    74.4 11.7: v       1    2
 23    45.5    72.6 14.7:  v     1     2
 24    44.0    71.1 16.5:  v     1    2
 25    43.5    69.7 17.5:   v    1    2
 26    44.2    68.5 17.5:   r    1    2
 27    44.9    67.5 17.5:   r    1    2
 28    45.5    66.7 17.5:   r    1   2
 29    46.0    66.1 17.5:   r    1   2
 30    46.4    65.7     :        1   2
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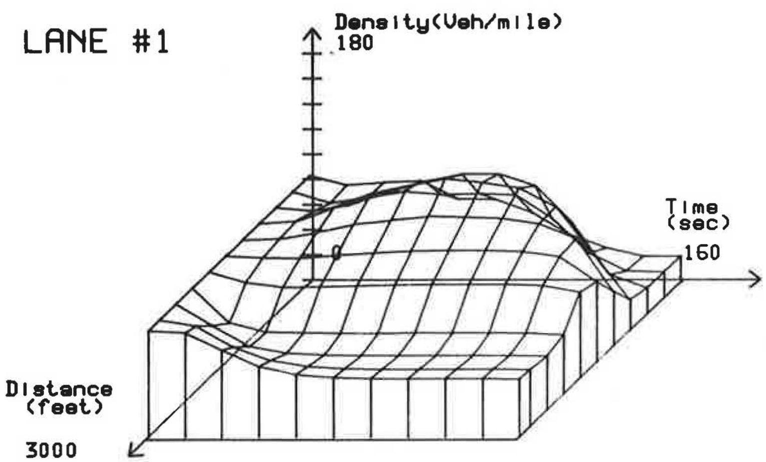
FIGURE 4 Density distribution by lane at t = 100 sec for the situation shown in Figure 3.



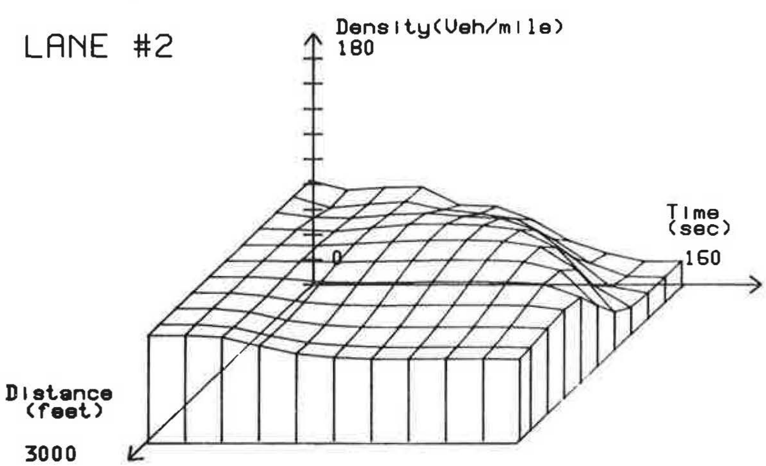


FIGURE 5 Graphic presentation of density in each lane as a function of time and space.

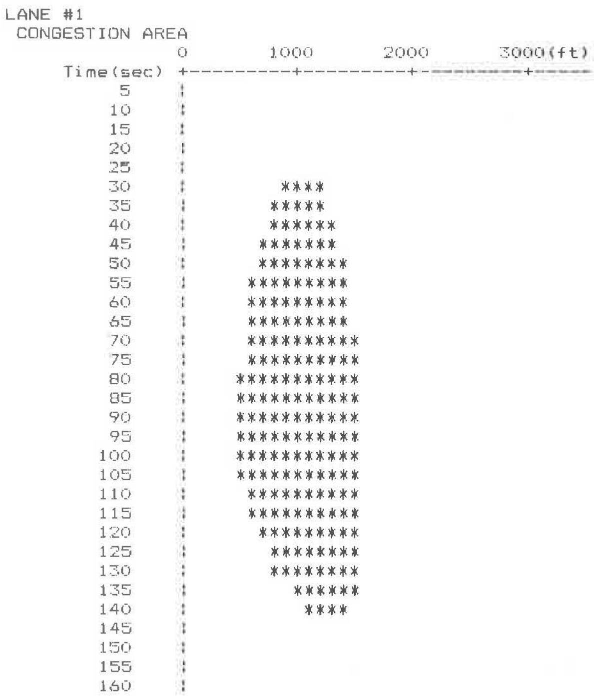


FIGURE 6 Graphic representation of congestion by lane in x and t.

the entire system and by zone as well as TTT, TT, delay, arrivals, departures, queue size and length, and the remaining measures of effectiveness and system statistics as described under General Program Capabilities. Extensions of the program allowing estimation of fuel consumption and pollution levels are currently under way.

HARDWARE AND PROGRAM LIMITATIONS

The memory of the computer currently used is 128K bytes; however, the usable memory with the existing IBM software (P-system) is actually only 34K bytes. Although new software is currently being prepared by IBM to correct this problem, the current 34K space restricts the size of the freeway sections that can be simulated. More specifically, this memory allows employment of up to 60 nodes; assuming a segment length Δx of 100 to 500 ft, this space allows simulation of freeway sections from 1.14 to 5.68 miles long.

Because the memory of the IBM-PC can easily be extended to 256K and possibly to 512K it is clear that the program's capability could be improved substantially even with existing IBM software (i.e., it could be quadrupled). Therefore, the maximum freeway length could be extended to 22.73 miles although in most practical applications the maximum length that needs to be analyzed rarely exceeds 10-12 miles. Longer segments could also increase the maximum length but this would imply lower accuracy. Further, as the number of lanes increases and separate statistics per lane are desired, maximum length decreases accordingly. For instance, for producing detailed statistics for two lanes, maximum length decreases by 50 percent, and conversely, if the results are aggregated, maximum length doubles. Incidentally, in its present form the program can handle up to three lanes; after this limit, all lanes must be combined or the program must be extended. This does not really present a problem if sufficient memory is available.

Execution time is a second consideration that might concern the potential user. Because of the limited capabilities of personal computers and the computations and bookkeeping required in simulation, execution time is generally long. Despite this, the effectiveness of the models and the solution algorithms result in satisfactory execution time especially when the magnitude of the tasks accomplished by the program is considered. For instance, for simulating a two-lane freeway section with one entrance ramp and 30 nodes per lane for 240 sec, initial execution time was 50 min. Although this time includes lane changing and separate statistics per lane, as well as the drawing of graphs on the graphics screen while presenting all computational details on the CRT, this timing performance was not considered satisfactory. Execution time was reduced by 50 percent when the compiled program was executed.

Further improvements with respect to execution time are currently being sought by employing the Intel 8087 processor that is designed to add fast and accurate floating point capability to the Intel 8088 processor, currently used by the IBM personal computers. The two chips with appropriate software (available from independent vendors) can reduce computation time from 5 to 20 times (14). Clearly such improvement is significant and should make using the program more attractive.

Although the maximum freeway length that can be simulated by KRONOS-1 may be somewhat restricted by the available memory size, no such restrictions exist with respect to the simulation period; that is, it can be as long as desired.

PROGRAM TESTING AND VALIDATION

Because of budget and manpower limitations, comparisons with field data were not made. However, the program was implemented to a number of situations that covered a wide range of the speed, flow, and density domain and included both entrance and exit ramps as well as multiple lanes. Subsequently, the results were compared against those obtained from microscopic simulation using INTRAS (3), a recently developed, well-documented, tested, and calibrated program. Microscopic simulation for generating a data base was further justified by the need to allow demands to fluctuate sufficiently over a controlled and frequently wide range in relatively short time intervals. Such intervals were sought for reducing the comparison effort. Another consideration justifying data base generation by INTRAS was the need to impose tractable initial and boundary conditions to allow intuitive inspection of the results.

Four of the initial test situations representing both uninterrupted and interrupted flow are shown in Figures 7, 8, and 9. All cases in these figures represent single-lane flow because it was thought that initial testing under the simplest flow conditions should prevent distortion of true model performance; distortion could be introduced from lane changing, especially in merging areas. Unsatisfactory program performance, even in this simple case, would imply that there is little reason to expect better results as the number of lanes increases. In case 1 (Figure 7a) demands are nearly constant approaching maximum flow. In case 2 (Figure 7b) flow starts at about one-third of its maximum value; subsequently, it gradually increases to the maximum flow rate where it remains for some time and then it gradually decreases to its initial level. In case 3, merging flows are introduced for a short time to

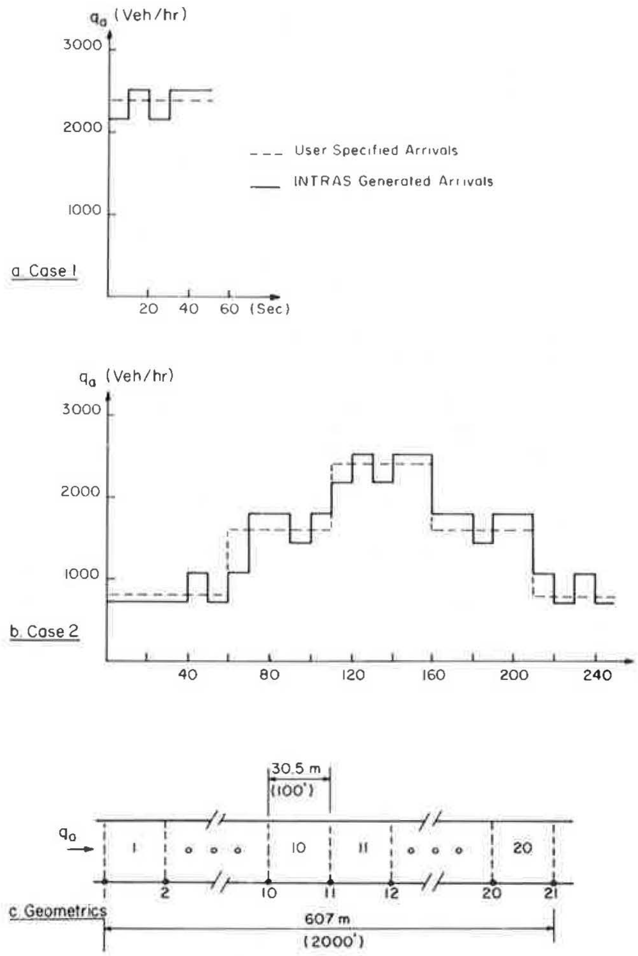


FIGURE 7 Arrival patterns and geometrics for uninterrupted flow testing (cases 1 and 2).

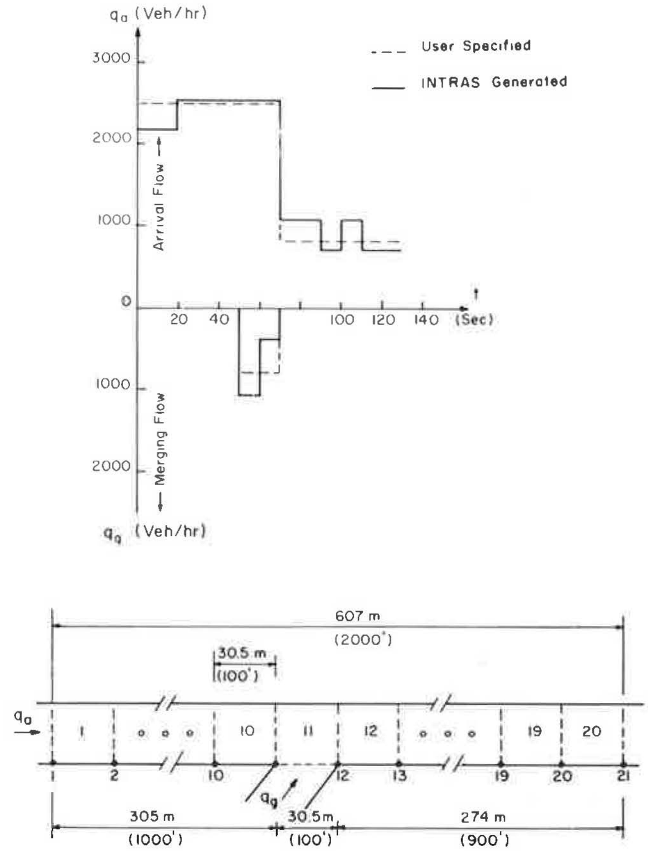


FIGURE 8 Input patterns and geometrics for interrupted flow (light congestion, case 3).

create light congestion. The demands drop substantially after congestion sets in for quick dissipation. Finally, case 4 is similar to case 3 but represents a longer freeway section and higher ramp demands for heavier congestion.

It should be noted that the merging flows shown in Figures 3 and 4 are the actual ones entering the freeway (i.e., not simply the ramp demands) and were obtained from INTRAS. Maximum freeway uninterrupted flow suggested by INTRAS was approximately 2,400 passenger car units per hour. This value may appear high compared with the maximum of 2,000 cars per hour usually employed in practice. It should be pointed out, however, that under nearly ideal conditions maximum flows of up to 2,300 vehicles per hour have been measured in practice (4). Because this figure includes some trucks and other heavy vehicles, it appears that the value obtained by INTRAS for passenger cars only is not unreasonable. Finally, in the KRONOS-1 simulations Δx and Δt were assumed to be 100 ft and 1 sec, respectively, and the free-flow speed was assumed to be 55 mph. Incidentally, the INTRAS estimates of q, k, and u were averaged over 10-sec intervals in every Δx increment to make meaningful comparisons. Final estimates (i.e., at the end of simulation) of total travel time (TTT) for the entire section under consideration were also compared. For the latter measure of effectiveness its percentage difference (PD) from the data was estimated and used as a criterion of close agreement; a negative PD indicates that the model overestimates TTT and positive PD indicates underestimation. In the comparisons of speed and density the mean absolute error (MAE) and mean square error (MSE) were employed. The former was defined as

$$MAE = (1/nxm) \sum_{i=1}^{m} \sum_{j-1}^{n} | z_j^i - \hat{z}_j^i |$$

where

- n = the number of space increments Δx (=100 ft),
- m = the number of 10-sec intervals corresponding to the entire simulation period,
- z_j^i = the average INTRAS estimate of speed flow and density over segment j and 10-sec interval i, and
- $\hat{z}_j^i$ = the average model estimate of speed flow and density over segment j and 10-sec interval i.

Using this notation the MSE is defined as

$$MSE = (1/nxm) \sum_{i=1}^{m} \sum_{j=1}^{n} (z_j^i - \hat{z}_j^i)^2$$

Finally TTT and TT were estimated by numerical integration of the expressions

$$TTT = \int_0^T N(t)dt$$

$$TT = \int_0^T \left[\sum_{\ell=1}^{N(t)} u_\ell(t) \right] dt$$

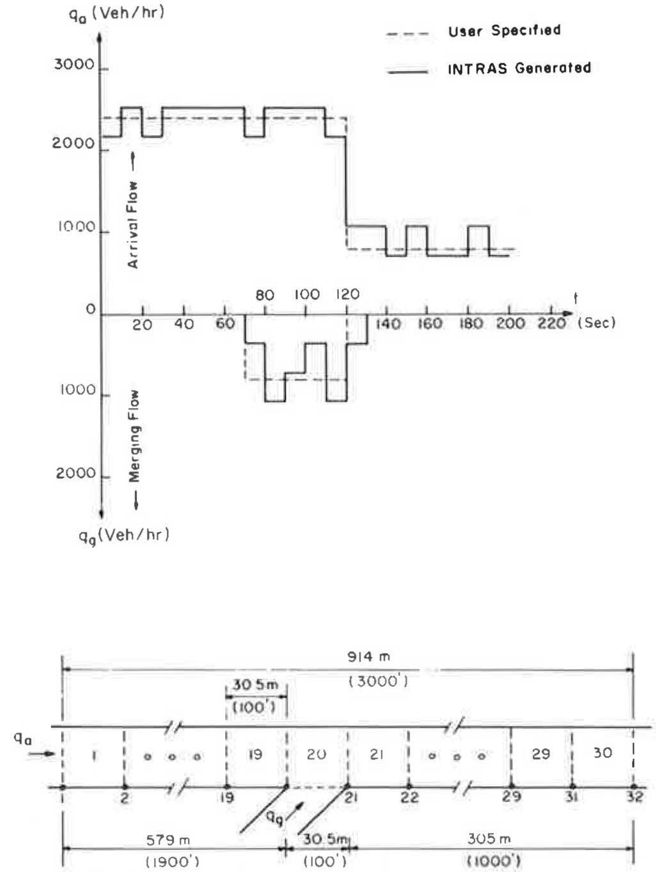


FIGURE 9 Input patterns and generation rates for case 4 (interrupted flow, heavier congestion).

where

T = the simulation time and
N(t) = the number of cars in the entire freeway section at an instant = $\int_0^L k(x)dx$.

In addition to MSE, MAE, and PD, visual comparisons of the KRONOS-1 results with the data base were made from the plots of q, k, and u versus time and space. Overall, the comparisons of the KRONOS-1 and INTRAS data were very satisfactory. This can be seen from the data in Table 1, which indicate that the error indices MSE, MAE, and PD are very small. For instance, the error in estimating TTT by KRONOS-1 ranges from 7.1 to 9.5 percent using the simple-continuum model (column 1). This error range is reduced to 3.6 to 6.7 percent by the hybrid model (column 2) and to 0.3 to 5.5 percent by employing a discontinuous v-k relationship (column 3). It is worthwhile noting that in further testing the error indices were reduced from 40 to 60 percent when the step size Δx and Δt was also reduced by one-half. A partial visualization of these comparisons is shown in Figure 10, which shows the distribution of density in case 4 (interrupted flow) at five time intervals during the simulation.

Further comparisons with multiple lanes and more than one entrance ramp were also made and the results were found equally satisfactory. Table 2 gives the comparisons of two additional situations representing uninterrupted and interrupted flow conditions on two-lane facilities, described in detail elsewhere (10). The first column corresponds to the simple-continuum model and the second to the high-order models; the third column is slightly different from the second in that the parameter T (reaction time) of the momentum equation of the high-order model was assumed to be a function of density. In the fourth column the results of the hybrid model are presented. According to the hybrid model, the momentum equation in a particular segment is dropped when congestion sets in. Column 5 corresponds to a two-dimensional model that explicitly includes street width (10). Columns 6-10 correspond to the case of interrupted flow and are similar to the first five.

As the data in Table 2 indicate, the error indices are very small and the differences among the various alternatives are not substantial. Figure 11 shows a comparison of the results obtained from the simple-continuum model in the uninterrupted flow case, and is similar to Figure 10. The INTRAS data correspond to the average of both lanes (INTRAS does not output lane-specific information). The per lane density estimates of KRONOS-1 are also shown, as well as the average value, which is very close to the INTRAS results. As before, the error levels could be substantially reduced by reducing the step size. Additional testing and evaluation results for multilane facilities are available (10) and they suggest close agreement with the INTRAS microscopic simulations.

CONCLUSIONS AND RECOMMENDATIONS

Perhaps the most interesting feature of the KRONOS-1 simulation program is that it can run on a microcomputer while its results closely agree to those of microscopic simulation, especially when the step size is reduced. This was made possible by the simplicity of the particular finite-difference methods used that allow quick calculation of the flow parameters k, u, and q in both time and space. The improved modeling employed by the program allows treatment of merging, diverging, and simple weaving sections. Therefore, despite the macroscopic nature of the program, acceleration, deceleration, and auxiliary lanes can be taken into account. This, combined with the simplicity of running the program, should encourage its use in even less complex problems such as estimating ramp capacity or level of service.

Although present execution time and the size of the freeway should be satisfactory for most practical applications, further improvements are possible. For instance, by incorporating the Intel 8087 processor into the personal computer it is anticipated that execution time will be reduced substantially (5-20 times); that is, it will be only a fraction of the simulation time. The size of the freeway should not present a problem, especially when expanded memory is employed. Enhanced memory will necessitate program extensions to allow a larger number of ramps and more than three main lanes when the lane changing option is selected. However, such extensions can easily be made. Further, it should be observed that software improvements currently under way at IBM should allow larger usable space without additional memory.

KRONOS-1 in its present form is only a prototype and as such it requires more rigorous testing and calibration. Such testing using field data and simulation results is currently under way. Practical extensions are also being implemented in a new version of the program called KRONOS-2. These extensions include simulation of ramp metering, estimation of fuel consumption and pollution levels, inclusion of trucks and other heavy vehicles, improved

TABLE 1 Error Indices of KRONOS-1 for the Simple Continuum and Hybrid Models

MOE	Case \ Model	Simple Continuum	Hybrid Model (Discont. u-k)	Simple Continuum (Discont. u-k)
k:	1	7.69 (91.04)*	8.48 (10.9)	7.41 (83.39)
Density	2	6.89 (80.72)	6.24 (64.37)	6.21 (63.97)
(Veh./Mi)	3	11.0 (234)	11.76 (238)	5.67 (49.20)
	4	11.8 (270)	11.53 (254)	9.68 (177)
u:	1	3.27 (17.83)	4.71 (37.13)	2.94 (12.60)
Speed	2	4.13 (27.89)	3.39 (16.72)	3.39 (16.78)
(Mi./Hr.)	3	7.21 (86.62)	10.4 (180)	2.69 (11.02)
	4	6.47 (77.62)	10.1 (169)	4.81 (43.14)
	1	11.24 (-7.1)	10.11 (3.6)	10.46 (0.3)
TTT	2	48.62 (-9.5)	46.02 (-3.7)	47.08 (-6.1)
(Veh.-Min.)	3	30.09 (7.9)	35.83 (-6.7)	33.82 (-3.5)
	4	89.65 (-8.2)	88.28 (-6.5)	87.39 (-5.5)

*Numbers indicate MAE (MSE) for k and u; in last MOE the numbers show the actual value of TTT and % difference from data.

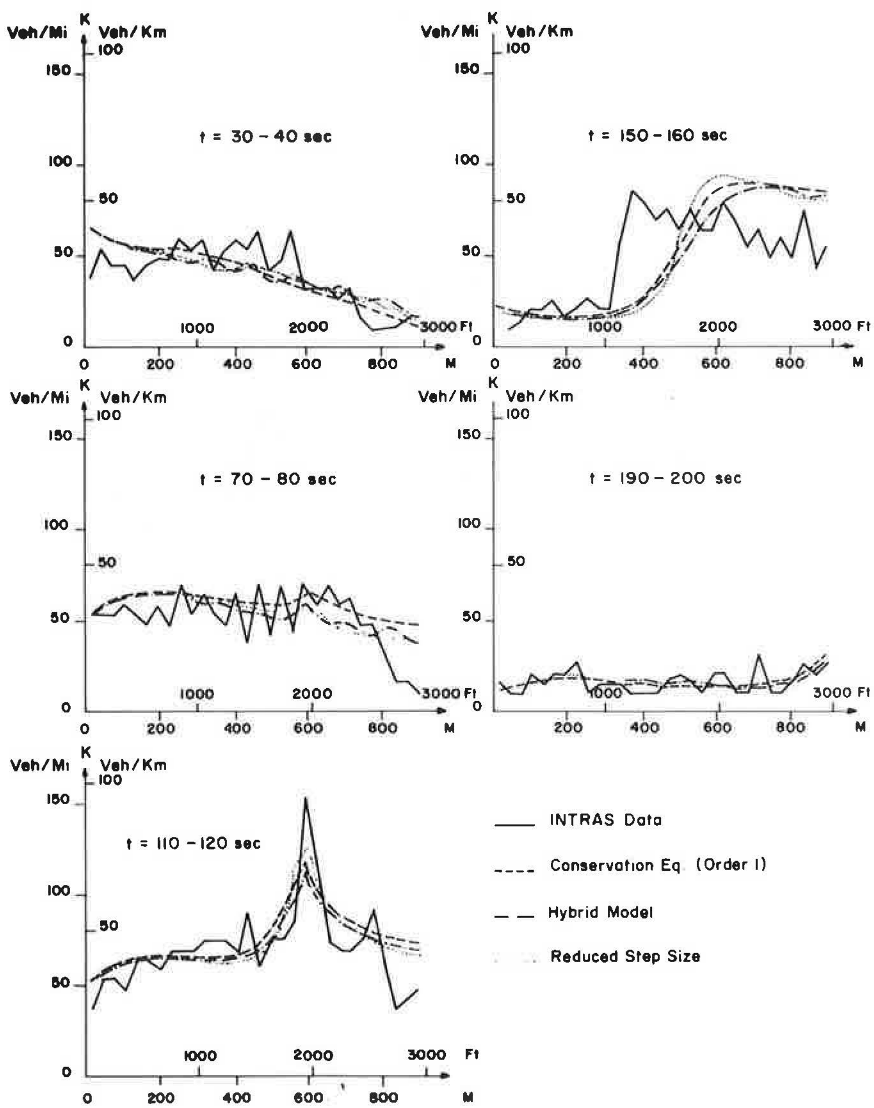


FIGURE 10 Comparison of KRONOS-1 and INTRAS results (case 4).

TABLE 2 Error Indices of Modeling Alternatives at Two-Lane Facilities When per Lane Estimates Are Averaged

Situation / Model / MOE	1. Uninterrupted Flow					2. Interrupted Flow				
	1 Simple Continuum	2 High Order T-cons	3 Modified High Order T=T(k)	4 Hybrid Model	5 2-D Model	6 Simple Continuum	7 High Order (Const. T)	8 High Order (Variable T)	9 Hybrid Model	10 2-D Model
Density (veh/mi)	2.06$^{(1)}$ (14.50)	2.07 (14.74)	2.21 (16.45)	2.22 (16.48)	2.38 (21.48)	6.76 (181)	7.30 (207)	6.91 (179)	6.81 (179)	6.84 (162)
Speed (mi/hr)	1.69 (8.88)	1.74 (9.46)	2.08 (12.63)	2.07 (12.59)	2.17 (13.65)	4.02 (55.3)	4.19 (60.0)	3.70 (48.8)	3.76 (48.5)	3.75 (47.5)
TTT (veh-min)	40.88$^{(2)}$ (-0.15)	40.53 (0.72)	38.86 (4.81)	38.88 (4.81)	36.95 (9.48)	230.1 (-2.56)	229.2 (-2.17)	204.1 (9.03)	217.3 (3.10)	228.5 (-1.85)

$^{(1)}$Numbers outside of parenthesis in k, u and q rows indicate MAE; # in parenthesis indicates MSE.

$^{(2)}$Number indicates estimated TTT while the number in parenthesis the % difference from INTRAS.

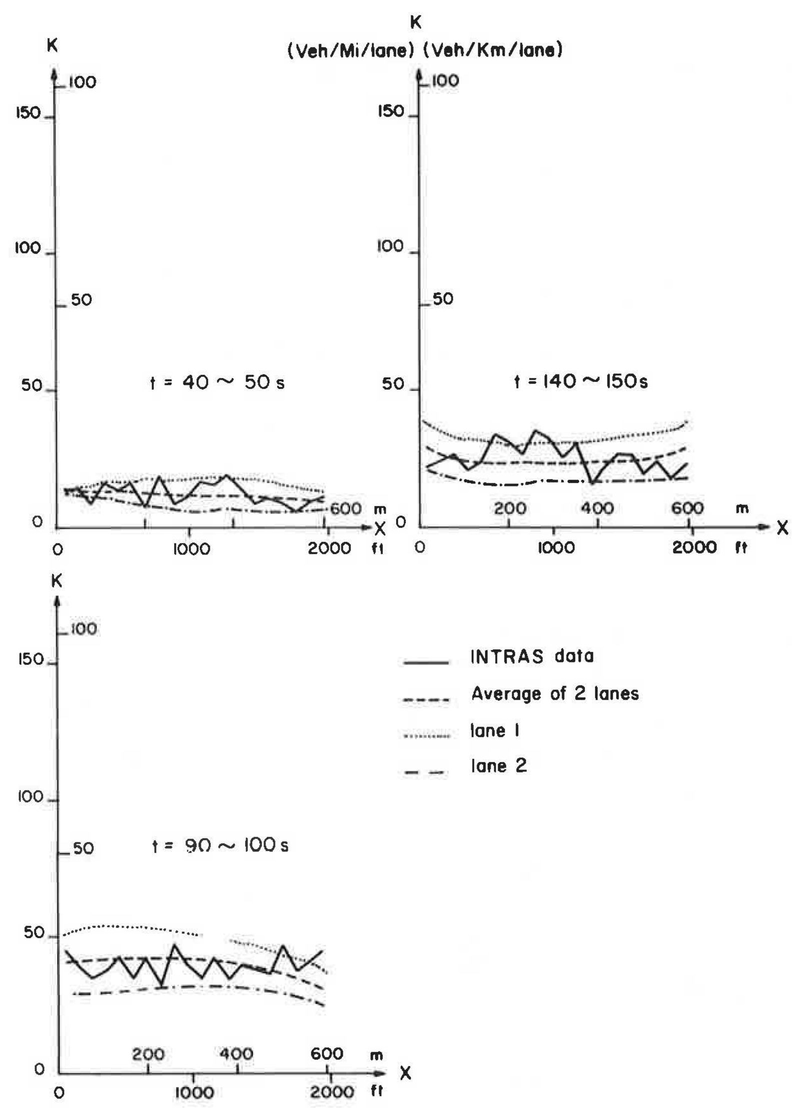


FIGURE 11 Comparison of KRONOS-1 and INTRAS results in a two-lane situation (uninterrupted flow, simple continuum model).

graphics and I/O operations, and so forth. KRONOS-2 is being developed for the Minnesota Department of Transportation and it should be completed in 1984.

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