LOGICAL DESIGN AND DEMONSTRATION OF UTCS-1 NETWORK SIMULATION MODEL

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A description is given of a microscopic simulation model designed as an evaluative tool for urban traffic control policies. The need for such a tool is explored, and the underlying benefits of the simulation approach are discussed. The logical structure of the model is described; the input requirements and statistical output generated by this FORTRAN-coded program are detailed, and samples are illustrated. The prominent features of the model are examined in detail.

•CONSIDERABLE attention has been devoted in recent years to the development of sophisticated control policies for application to networks of urban traffic signals. The need for such advanced control policies is evidenced by the growing volume of vehicular and pedestrian traffic in urban environs and the resulting congested conditions that threaten the viability of urban transportation systems. Improving the effectiveness of traffic control appears to hold the greatest near-term potential for relieving those conditions that impede the flow of traffic and act to constrict the economic and social activities of urban areas.

The design of such control policies and their implementation on urban networks represent a considerable investment in manpower and in hardware. The implemented control policy, the traffic demand, and the urban roadways constitute a complex system that is not amenable to closed-form mathematical analysis. The design of the various components of this system—surveillance detectors, communication network, signal controllers, digital computer configuration, control policy design, software package—interact with one another in complex ways that are difficult to evaluate a priori.

It is not practicable to adopt a "try-something-and-see" policy for such a system. The selection of a digital computer and the choice of detectors (their number and placement) are decisions involving a considerable capital investment, which are strongly related to the design of the control policy to be implemented. It appears, then, that some analytical technique is required that can evaluate alternative control policy designs for the environment under consideration. The development of the UTCS-1 simulation model is an outgrowth of the need to fill this requirement.

The design of the UTCS-1 model for the study of urban traffic flow and dynamic signal control systems was directed to satisfy the following objectives: The model must accurately describe the real-world dynamics of urban traffic and respond to a wide variety of controls, including responsive systems actuated by an on-line digital computer. This description of traffic dynamics must be expressed in terms of significant traffic parameters and measures of effectiveness that characterize the performance of each component (link and node) of the network. The accuracy and reliability of these results must satisfy the basic research objective of utilizing the model as a diagnostic engineering tool for the evaluation of alternative policies of traffic control, channelizations of traffic, and turning and parking restrictions for any urban network configuration and composition of traffic, including buses.

The model must accurately describe individual responses to the constraints imposed by the control system, geometrical configuration, competing traffic elements (vehicular and pedestrian), and operating characteristics of the vehicle. The vehicles within the system must be treated as a collection of independently motivated entities, interacting with the urban network environment. Hence, a discrete, stochastic, microscopic simulation model is required.

Such a model requires a balance between considerations of sufficient detail to accurately describe the system and considerations of practical utility, e.g., cost of operation and need to satisfy storage restrictions of available computers. Furthermore, to promote wide acceptance of the resulting computer program requires that a high-level programming language acceptable to all computers regardless of manufacturer be employed. To further promote the use of the program requires that the substantial costs of data acquisition and preparation be reduced to a minimum. In addition, the program must be structured as a logical synthesis of closed routines such that most modifications will affect a minimum number of these routines.

The UTCS-1 program was designed to satisfy the requirements and objectives described above and was oriented to serve the needs of the practicing traffic engineer. The model also serves the needs of future research activities, the design of surveillance systems, and the development of computer software to implement traffic control policies.

The following subsections include a discussion of computer simulation and a detailed exposition of the features that are embodied in the UTCS-1 model (1).

RATIONALE FOR COMPUTER SIMULATION

Simulation is a modeling process that permits the study of a complex, dynamic system that cannot be adequately described by mathermatical relations alone. It is of particular value when the system under study comprises components that are highly variable and must be described in probabilistic terms through the medium of distribution functions. The advantage of a simulation model, properly calibrated and validated, is its use as a test-bed to economically study the system's dynamic response to a variety of input specifications.

The general attributes of simulation models may be summarized as follows:

1. Simulation permits the study and experimentation of the complex internal interactions of a system;
2. Detailed study of the simulation results provides a better understanding of the system and leads to improvements in its operation;
3. Simulation of a complex system yields valuable insight into those components that most profoundly affect the system's performance, identifies those that are less sensitive in this respect, and promotes an understanding of how these components interact with one another;
4. A simulation model may be used to experiment with new concepts that have yet to be put into practice and to test new policies and decision rules for operating a system before resources are committed for developing them;
5. The process of creating the simulation model requires that the system be "fragmented" into its component parts, each of which may be amenable to successful analytic formulations;
6. A simulation study is less costly than most other forms of experimentation; and
7. Simulation is safe, for the system can be tested by the computer rather than in a real situation where the possible creation of hazardous conditions would be infeasible.

A simulation model may be classified as either microscopic or macroscopic. The latter type is designed to yield the global behavior patterns of the system under study and does not require the detailed mechanisms of each component to be deeply probed as does the former type. In other cases, the intrinsic assumptions associated with the design of a macroscopic model completely invalidate its integrity. For an urban traffic system, it is mandatory that the model be designed to properly replicate the microscopic dynamics of the system component, in order to produce results that accurately reflect real-world behavior.

In summary, a system that functions dynamically as a complex logical interaction of many small components, some of which are stochastic and are characterized by rapidly changing conditions, is a prime candidate for simulation modeling for the purpose of analysis and eventual design.

FEATURES OF UTCS-1 MODEL

The UTCS-1 model has the following features:

1. Representation of any urban network having as many as 100 intersections and associated input and output links;
2. Simulation of the full range of geometric configurations found in the central areas of U. S. cities of 50,000 population or more;
3. Replication of traffic performance under all forms of network traffic control, including dynamic control systems based on the area-wide surveillance of traffic parameters such as traffic volume, average speed, traffic density-vehicle content, and smoothness of flow;
4. Provision for a flexible mix of both input and output options (standard output measures that may be accumulated by cycle or any larger time period for both an individual intersection and the network as a whole include link volume, average link speed, average link travel time, total vehicle-miles of travel, traffic density-vehicle content, vehicle delay, queue length, number of stops, and smoothness of flow);
5. Stochastic simulation of individual vehicles by type, utilizing a simplified car-following model, time-scanning methods, and 1-sec memorandum notation;
6. Detailed treatment of both intersection and intralink behavior, including queue discharge and turning behavior, intersection "spillback," pedestrian-vehicular traffic interaction, and intralink acceleration and deceleration;
7. Treatment of nonsignalized controls, e. g., STOP and YIELD signs, free-force merge, and exclusive channelization (e. g., turning lanes);
8. Treatment of bus traffic, including specification of bus routes, bus stop-dwell times, and bus-vehicular traffic interaction;
9. Treatment of intralink friction, including both legal and illegal parking, parking garage flows, and intralink rare events (e. g., cab pickups, delivery vehicles, and temporary lane closure);
10. Simulation of alternative surveillance systems, including location and type of detector (e. g., presence detector, counter, and spot speed detector), detector signals, and detector reliability (as many as 3 detectors may be utilized per lane and as many as 12 per link);
11. Provision for minimum essential input data to simulate a given set of field conditions, including allowance for both location-specific and phenomenological (i. e., network-wide) data inputs, and provision for a comprehensive set of default options-values;
12. Description of traffic network at varying levels of detail and specificity; and
13. Provision for internal control of network "fill-time."

MODEL STRUCTURE

An urban street network is decomposed for the purpose of model operation into a network of unidirectional links (streets) and nodes (intersections), as shown in Figure 1. Each link may contain as many as 5 moving lanes. Wider streets may be accommodated by an individual street being separated into 2 successive links. Intersection control may take the form of 9 different signal configurations, including STOP and YIELD sign control. As many as 9 signal phases may be incorporated into any given signal cycle. Provision is made for the simulation of alternative surveillance systems, incorporating as many as 3 detectors in any 1 lane and as many as 12 detectors in total for any 1 link. The information derived from these detectors may in turn be used as input to alternative traffic-responsive network control strategies.

Vehicles are emitted onto the network along entry links or from "source" nodes located within the interior of the network. In addition, "sink" nodes may extract traffic from specified links within the network. These source and sink nodes serve to represent the operation of parking lots, garages, or service stations or of intermediate streets not represented on the full simulated network. Traffic is discharged from the network via exit links or through the sink nodes described above.

Each vehicle is uniquely identified in terms of its performance characteristics and is simulated as an individual entity. Its time-space trajectory as it traverses the network is recorded to a resolution of 0.1 sec. Associated with each vehicle is a table that is updated every second, so that a record is maintained of the vehicle's statistical history. This record includes specification of the type of vehicle (e.g., automobile, truck, or bus), cumulative trip time, cumulative distance traveled, cumulative delay incurred, current lane and link position, projected turning movement at the downstream intersection, number of stops incurred to date, and current position in queue. Hence, the complete trajectory history and the current status of each vehicle on the network are known at any given point in time. The data contained within these "vehicle arrays" are interrogated by the various subroutines in the model and are also periodically accumulated and displayed as output.

The simulation of separate vehicles as individual entities permits the accurate formulation of a series of microscopic components of the model dealing with phenomena such as turning logic at intersections, queue discharge, and lane-switching. This in turn is the basis for the provision within the model system of a wide spectrum of features that otherwise could not be treated directly, e.g., the treatment of bus traffic with specified routes and midblock bus stops, and that are essential if the model is to accurately reflect the response of real-world traffic behavior to alternative network control strategies.

The model is programmed completely in FORTRAN IV and is operational on both CDC 6600 and IBM 360 hardware. It consists of 43 separate subroutines, including a central executive routine, UTCS-1, which is used to activate the other subroutines in logical sequence. The central UTCS-1 routine is executed once each "time step" throughout the simulation. Provision is also made for updating selected inputs to the model, including specification of signal-timing and input-flow rates at the start of each of a series of regular "subintervals" within the overall simulation run. Figure 2 shows the logical flow for the main UTCS-1 routine.

INPUT REQUIREMENTS

The model has been designed to meet a number of specific objectives concerning input data requirements. These include the following:

1. Minimization of the necessary information required for the simulation of a given network or a given set of traffic conditions;
2. Utilization, to the maximum possible extent, of data that are normally available in the files of traffic engineering departments;
3. Through the medium of input options, restriction of input data to those that are directly relevant to the needs of the user;
4. Provision for the effective utilization of varying levels of input data, depending on the quantity and the quality of the information available to the user; and
5. Provision for default information for use in those instances where specific calibration information cannot be obtained for a particular network.

Within the framework defined by these objectives, the necessary set of input data required to operate the model may be grouped under 2 separate headings: location-specific parameters, reflecting the particular characteristics of a given network link or intersection, and phenomenological measures, which are assumed to remain constant across the entire network to be simulated, regardless of the location of a specific link or intersection.

Specifically, the following input data are required:

1. For each network link, number of moving lanes, length, capacity of left-turn pocket, desired free-flow speed, mean queue discharge rate, turning movements at downstream node, identification of receiving links, pedestrian volume, and lane channelization;
2. At each intersection complete specification of signal (or sign) control, including sequence and duration of each phase and identification of signal facing each approach;

Figure 1. Validation network.

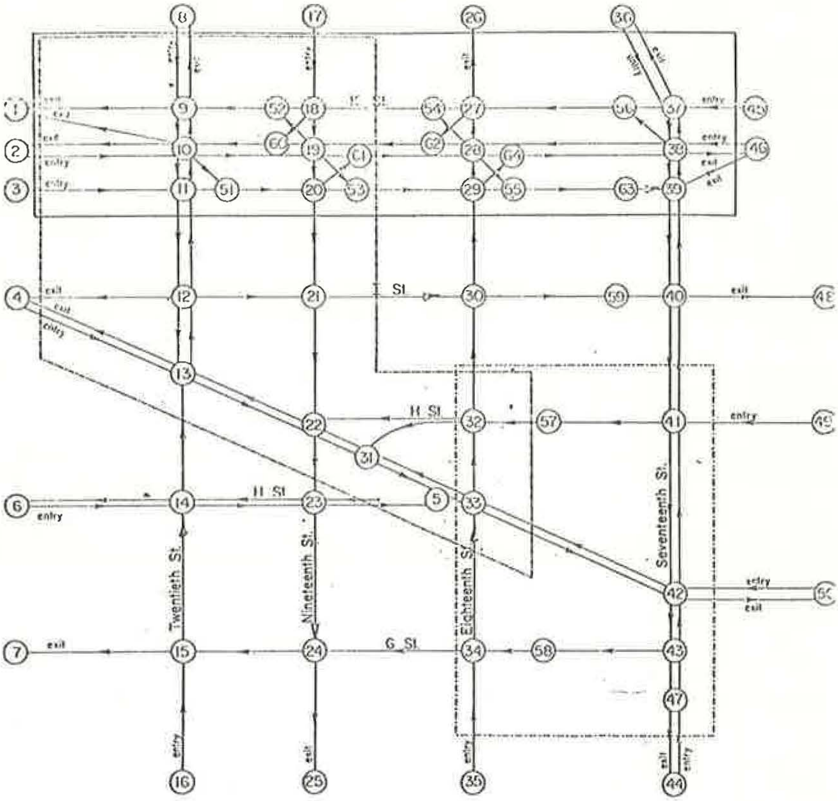
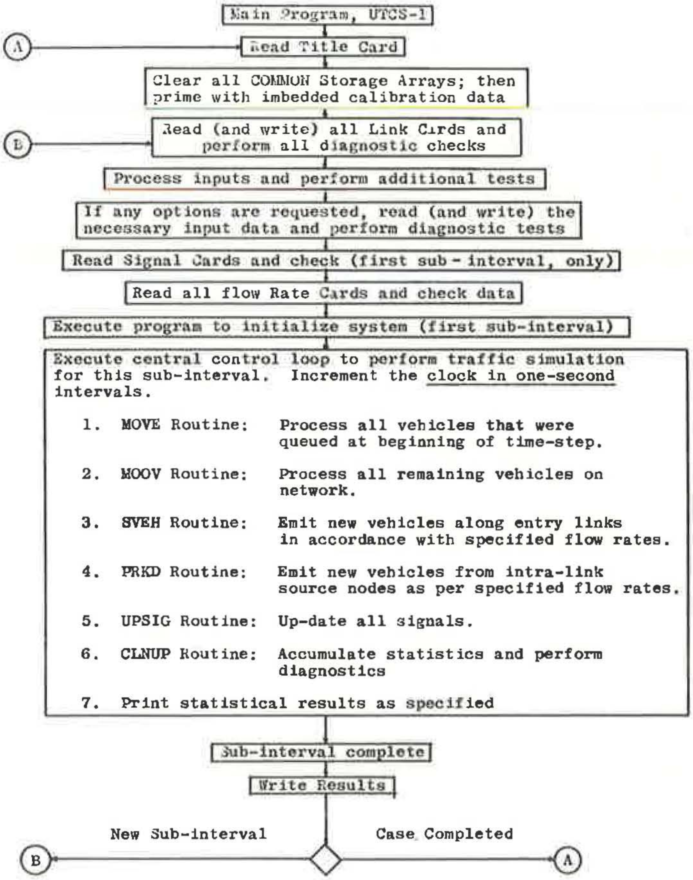


Figure 2. Logic flow for UTCS-1 executive routine.



Main Program, UTCS-1

Read Title Card

Clear all COMMON Storage Arrays; then prime with imbedded calibration data

Read (and write) all Link Cards and perform all diagnostic checks

Process inputs and perform additional tests

If any options are requested, read (and write) the necessary input data and perform diagnostic tests

Read Signal Cards and check (first sub-interval, only)

Read all flow Rate Cards and check data

Execute program to initialize system (first sub-interval)

Execute central control loop to perform traffic simulation for this sub-interval. Increment the clock in one-second intervals.

1. MOVE Routine: Process all vehicles that were queued at beginning of time-step.
2. MOOV Routine: Process all remaining vehicles on network.
3. SVEH Routine: Emit new vehicles along entry links in accordance with specified flow rates.
4. PRKD Routine: Emit new vehicles from intra-link source nodes as per specified flow rates.
5. UPSIG Routine: Up-date all signals.
6. CLNUP Routine: Accumulate statistics and perform diagnostics
7. Print statistical results as specified

Sub-interval complete

Write Results

New Sub-interval

Case Completed

Figure 3. Link input data.

```
                                   MEAN          TURNING INCIDENCES      DESTINATION NODES             PED   LANE USAGE
   LINK   LANE   SPAN   LTRN   U F      H     LEFT THRU RIGHT DIAG    LEFT THRU RIGHT DIAG    LOST DEN   1 2 3 4 5   TYPE   L
( 23, 16)   2     86      0     24     24       0  100     0    0       0   27     0    0       0    0   0 0 0 0 0     1    19
( 16, 27)   2    590      0     28     24       0   59    41    0       0   14    26    0       0    0   4 0 0 0 0     1    20
( 27, 14)   2     50      0     28     24       0  100     0    0       0   18     0    0       0    0   0 0 0 0 0     1    21
( 14, 18)   2    447      0     28     24       0  100     0    0      19    6     0    0       0    0   0 0 0 0 0     1    22
( 18,  6)   2     50      0     28     24       0  100     0    0       0    9     0    0       0    0   0 0 0 0 0     1    23
(  6,  9)   2    353      0     28     24       0   46    54    0      10    1     8    0       0    0   4 0 0 0 0     1    24
( 24, 28)   2    645      0     28     24       0   86     0   14       0   19    27   14       0    0   0 0 0 0 0     1    25
( 28, 19)   2    497      0     28     24       0  100     0    0      20   10     0    6       0    0   0 0 0 0 0     1    26
( 19, 10)   2    403      0     28     24       0   91     0    9      11    2     9    1       0    0   0 0 0 0 0     1    27
( 10, 19)   2    415      0     28     24       0  100     0    0       0   28    20    7       0    0   0 0 0 0 0     1    28
( 19, 28)   2    495      0     28     24       0   92     0    8      27   24     0   15       0    0   0 0 0 0 0     1    29
( 28, 24)   2    620      0     28     24       0  100     0    0      23   32    25    0       0    0   0 0 0 0 0     1    30
( 11,  5)   2     50      0     28     24       0  100     0    0       0   20     0    0       0    0   0 0 0 0 0     1    31
(  5, 20)   2    365      0     28     24       0   32    68    0       0    7    21    0       0    0   4 0 0 0 0     1    32
( 20,  7)   2     50      0     28     24       0  100     0    0       0   29     0    0       0    0   0 0 0 0 0     1    33
(  7, 29)   2    445      0     28     24       0  100     0    0      28   15     0    0       0    0   0 0 0 0 0     1    34
( 29, 15)   2     50      0     28     24       0  100     0    0       0   34     0    0       0    0   0 0 0 0 0     1    35
( 34, 25)   2    250      0     28     24       0   50    50    0      24   32    33    0       0    0   4 0 0 0 0     1    36
( 15, 34)   2    320      0     28     24       0  100     0    0       0   25     0    0       0    0   0 0 0 0 0     1    37

                                   THIS NETWORK CONTAINS A TOTAL OF  58 LINKS

                                          PEDESTRIAN DENSITY CATAGORIES

                        LIGHT DENSITY DENOTES A RANGE OF PEDESTRIAN VOLUME OF   0-200 PEDS./HOUR

                             MODERATE,  200-500 PEDS./HOUR.  HEAVY,  ABOVE 500 PEDS/HOUR
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Figure 4. Traffic signal data.

```
INITIAL PHASE AT NODE  5 IS 1.  TIME REMAINING  0 SECONDS


NODE    5            PHASE  1           DURATION  80 SECONDS
         SIGNAL FACING LINK ( 11,  5) IS (CODE) 1
         SIGNAL FACING LINK ( 10,  5) IS (CODE) 1


INITIAL PHASE AT NODE  6 IS 1.  TIME REMAINING  0 SECONDS


NODE    6            PHASE  1           DURATION  80 SECONDS
         SIGNAL FACING LINK ( 18,  6) IS (CODE) 1
         SIGNAL FACING LINK ( 19,  6) IS (CODE) 1
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Figure 5. Traffic demand data.

```
                         ENTRY LINK STATISTICS


  LINK                       FLOW RATE (VEH/HR)                PCT. TRUCKS


(  2, 10)                          780                            8

(  3, 11)                          375                            4

( 12, 11)                          750                            4

( 30, 29)                         1110                            0

( 33, 25)                         1095                            1

( 32, 24)                          585                            0

( 31, 23)                          300                            0

( 22, 23)                          810                            0

( 17, 18)                          705                            4

(  8,  9)                          285                            5

(  6,  9)                          -30                            0     PSEUDO-LINK


  THERE ARE 10 ENTRY NODES AND  1 SOURCE/SINK NODES IN THIS NETWORK

                 MAXIMUM INITIALIZATION PERIOD=-240 SECONDS.
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Figure 6. Link output data.

```
             VEH-    VEH   MOV.   DELAY         TOTAL  T-TIME  T-TIME/    D-TIME   D-TIME/    AVG.   AVG.   STOPS  AVG   MSTPS CYCL
  LINK       MILES   DIS   TIME   TIME    M/T   TIME   / VEH.  VEH-MILE   / VEH    VEH-MILE   SPEED  OCC.   /VEH   SAT   /VEH  FAIL
                           V-MIN  V-MIN         V-MIN   SEC    SEC/MILE    SEC     SEC/MILE   MPH                  PCT
( 23, 16)     .3     19     .7     .6    .52     1.3     4.0    265.7       1.9     126.2      13.5     .3     .11 161   0.00     0
( 16, 27)    2.8     25    6.4   13.6    .32    20.0    48.0    429.3      32.6     291.3       8.4    4.9   1.26  10   0.00     0
( 27, 14)     .2     23     .5     .6    .41     1.1     2.9    304.9       1.7     178.6      11.8     .2     .13 134   0.00     0
( 14, 18)    2.5     29    5.4    2.3    .70     7.7    15.9    187.6       4.8      56.5      19.2    1.9     .23   5   0.00     0
( 18,  6)     .3     30     .6     .4    .59     1.0     2.1    228.4        .9      93.8      15.8     .2    0.00  18   0.00     0
(  6,  9)    1.7     26    3.8    9.3    .29    13.1    31.4    468.9      22.3     333.7       7.7    3.3     .81  11   0.00     0
( 24, 28)    4.4     36    9.1   18.2    .33    27.2    45.4    372.4      30.3     248.2       9.7    6.9     .87  14   0.00     0
( 28, 19)    3.4     36    7.3    4.3    .63    11.7    19.4    206.6       7.2      76.5      17.4    2.8     .35   7   0.00     0
( 19, 10)    3.1     41    6.3   13.1    .32    19.4    28.4    372.0      19.2     251.9       9.7    4.9     .62  16   0.00     0
( 10, 19)    4.2     54    8.9   10.2    .47    19.1    21.2    270.9      11.3     144.2      13.3    4.8     .55  15   0.00     0
( 19, 28)    4.7     50   10.7    7.0    .60    17.7    21.3    226.9       8.4      90.0      15.9    4.4     .36  11   0.00     0
( 28, 24)    5.9     50   11.7    3.8    .76    15.5    18.6    158.8       4.6      38.8      22.7    3.9     .12   8   0.00     0
( 11,  5)     .2     24     .5     .9    .37     1.4     3.4    370.9       2.2     233.0       9.7     .3     .13 170   0.00     0
(  5, 20)    1.9     28    4.3    2.3    .65     6.6    14.1    203.6       4.9      70.7      17.7    1.6     .21   5   0.00     0
( 20,  7)     .1     13     .3     .1    .79      .3     1.6    167.3        .3      34.9      21.5     .1    0.00  46   0.00     0
(  7, 29)    1.1     13    2.4     .9    .72     3.4    15.5    184.3       4.3      51.1      19.5     .9     .31   2   0.00     0
( 29, 15)     .1     14     .3     .2    .57      .5     2.2    235.9        .9     102.3      15.3     .1    0.00  67   0.00     0
( 34, 25)     .8     16    1.9    8.4    .18    10.2    38.3    808.2      31.3     661.6       4.5    2.6     .96  12   0.00     0
( 15, 34)    1.2     19    2.3    1.5    .60     3.8    12.1    199.9       4.8      79.2      18.0    1.0     .21   4   0.00     0
                                                          NETWORK STATISTICS

     VEHICLE-MILES=  44.38      VEHICLE-MINUTES=   205.9      VEHICLES PROCESSED=     467      STOPS/VEHICLE=  .59

   MOVING/TOTAL TRIP TIME= .473   AVG. SPEED (MPH)=12.93   MEAN OCCUPANCY=  50.6 VEH.   AVG DELAY/VEHICLE= 14.05 SEC

       TOTAL DELAY=  108.5 MIN.         DELAY/VEH-MILE= 2.44 MIN/V-MILE        TRAVEL TIME/VEH-MILE= 4.64 MIN/V-MILE
```

Figure 7. Bus data.

```
   LINK          NUMBER PROCESSED    MOVING TIME         DELAY TIME         M/T          NUMBER OF STOPS
                                         MIN                MIN

( 9, 10)              3                  .0                  .3             .08                2
( 23, 16)             4                  .2                  .2             .47                1
( 16, 27)             3                 1.0                 3.7             .22                8
( 27, 14)             3                  .1                  .2             .24                0
( 14, 18)             3                  .6                 1.5             .27                3
( 18,  6)             3                  .1                  .2             .24                0
(  6,  9)             3                  .5                 1.9             .21                4
( 24, 28)             3                  .5                 2.5             .15                4
( 28, 19)             2                  .5                 1.4             .27                3
( 19, 10)             3                  .3                 1.8             .13                2
    STATION               LINK         TIME CAPACITY EXCEEDED      TIME EMPTY       BUSES SERVICED
                                                MIN                   MIN

       1               ( 16, 27)                0.0                   2.7                 4
       2               ( 24, 28)                0.0                   3.1                 2
       3               ( 16, 27)                0.0                   3.0                 3
       4               ( 24, 28)                0.0                   2.9                 3
       5               ( 28, 19)                0.0                   3.3                 2
       6               (  6,  9)                0.0                   3.1                 2
ROUTE               BUSES PROCESSED    TOTAL MOVING TIME    TOTAL DELAY TIME    TOTAL DWELL TIME    AVG. SPEED
                                              MIN                  MIN                 MIN              MPH

  1                        2                  1.3                  4.6                 3.6              8.3
  2                        2                  1.1                  3.6                 1.1              7.6
  4                        3                  1.8                  4.6                 1.6              8.1
  5                        3                  1.5                  6.9                 2.9              8.9
  6                        0                  0.0                  0.0                 0.0              0.0
  7                        1                   .7                  1.5                  .3             11.2
                           SEED FOR RANDOM NUMBER GENERATOR IS    67367901
```

3. Traffic demand specified as flow rate (vph), percentage of trucks emitted onto the network along input (entry) links and from internal source nodes, and rate of extraction of vehicles at sink nodes;
4. Duration of simulation subintervals and specification of output options; and
5. As an option, specification of bus systems (routes, stations, mean headways, and mean dwell times) and frequency and duration of events, i. e., vehicles or conditions that block moving lanes of traffic.

MODEL OUTPUT

The user is provided considerable flexibility in specifying type and frequency of output data. All input data are printed out by the model for checking purposes. More than 50 diagnostic tests are performed, searching for inconsistencies in the input data; appropriate messages are printed identifying such errors before the program aborts. Figures 3, 4, and 5 show representative printed formats of the input data as produced by the program. Figure 6 shows cumulative statistics that are printed at the end of each simulation subinterval and more frequently if requested. The data provided for each network link and also aggregated for the entire network are as follows:

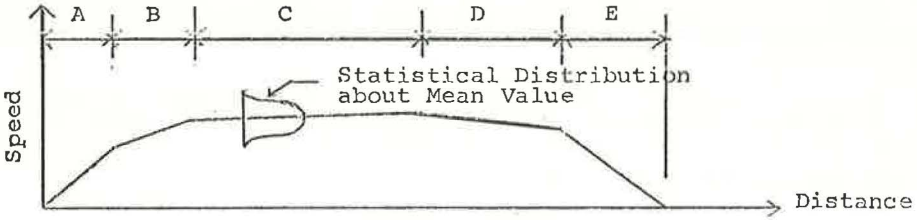
1. Link identification, by origin and destination node;
2. Estimate of total vehicle-miles of travel;
3. Count of total vehicles discharged;
4. Total vehicle moving time (at free-flow speed) in vehicle-minutes;
5. Total delay time computed as the difference between total travel time and ideal travel time based on target speed for link, in vehicle-minutes;
6. Ratio of moving time at desired speed to total\travel time;
7. Total travel time in vehicle-minutes;
8. Average travel time per vehicle in seconds;
9. Average travel time per vehicle-mile in seconds per mile;
10. Average delay time per vehicle in seconds;
11. Average delay time per vehicle-mile in seconds per mile;
12. Average traffic speed in mph;
13. Average occupancy (population) in number of vehicles;
14. Percentage of vehicles stopping at least once, expressed as a decimal;
15. Average saturation percentage, expressed as the average over time of the portion of the link that is occupied by vehicles divided by its total storage capacity;
16. Total number of cycle failures, defined as the number of times queue fails to clear from the discharge end of the link during a green period; and
17. Ratio of number of vehicles stopping more than once in a link to the total number of vehicles processed.

More detailed data delineating the variation of queue length with time and signal phasing may also be (optionally) requested. If buses populate the network, the model provides detailed statistics related to bus performance, as indicated in Figure 7. Another option provides origin-destination volumes. A typical network is shown in Figure 1. An assortment of "flags" or messages focuses the user's attention on extreme conditions. For example, the message, SPILLBACK BLOCKS 2 LANES ON LINK (11, 10) AT 5 14 36, denotes a condition of excessive queuing that restricts vehicles from discharging from the afflicted link.

INTRALINK VEHICLE MOVEMENT

Because the model processes each vehicle on the network, it is possible to replicate in detail those events that occur along the streets between intersections. Hence, interaction of automobiles with buses leaving stations, impact of double-parkers, disperison of platoon, and other intralink activities may be modeled rigorously, as opposed to an idealized specification of a constant "target" speed that is unrealistic and compromises the integrity of the simulation approach.

To implement this approach, we developed a simplified car-following expression and assumed that there was an idealized form of speed profile.



The 5 phases of a typical (unimpeded) speed profile were calibrated according to the Traffic Engineering Handbook:

1. Vehicle accelerates from rest to a speed of 20 ft/sec: a value of 8 ft/sec^2 for automobiles and 3 ft/sec^2 for buses and trucks;
2. Vehicle accelerates to free-flow speed: a value of 4 ft/sec^2 for automobiles and 2 ft/sec^2 for others;
3. Unimpeded vehicle maintains stochastically assigned free-flow speed until it either responds to a lead vehicle or recognizes that it must stop;
4. Vehicle initially decelerates essentially to a nonpowered cruise of -1 ft/sec^2; and
5. Vehicle decelerates to stop at -7 ft/sec^2.

Vehicles are constrained, of course, by the trajectory of any lead vehicle. Hence, a car-following law that is superposed onto (and supersedes) the speed profile described above had to be developed. Initially, finite-difference representations of the classic differential car-following equations were considered and found wanting for this model. Instead, a model tailored to the program logic was developed, and that led to the following equation:

$$a_f = [7(s_\ell - s_f - V_{f1} \cdot \Delta t - L_\ell) + \tfrac{1}{6}(2V_\ell^2 - 3V_{f1}^2)]/(V_{f1} + 3) \qquad (1)$$

where

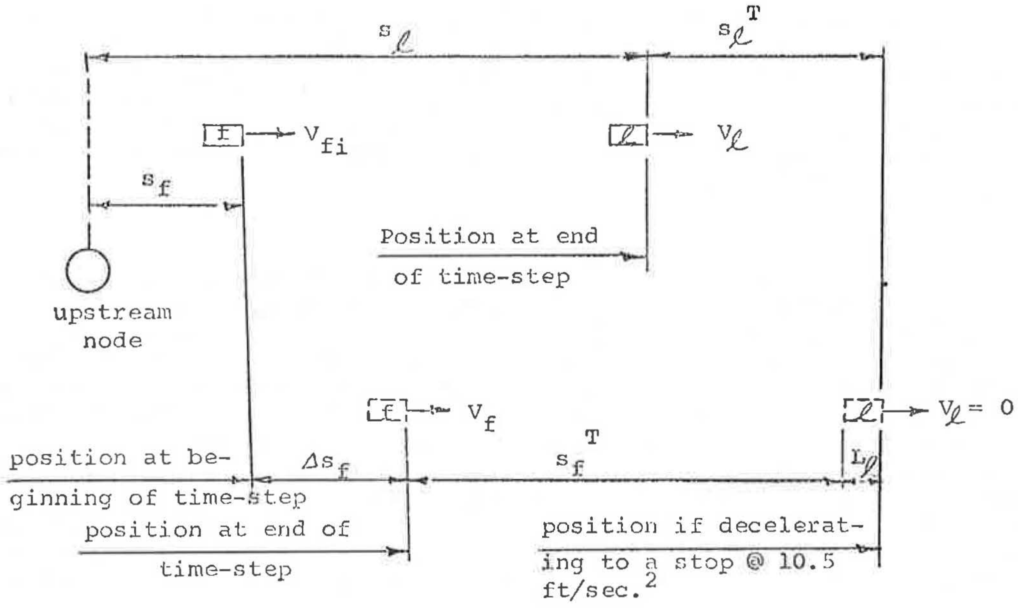
a_f = acceleration of the following vehicle now being processed;
Δt = simulation time step = 1 sec;
V_{f1} = speed of following vehicle at beginning of this time step;
V_ℓ = speed of lead vehicle at end of this time step;
L_ℓ = effective length of lead vehicle;
s_ℓ = distance of lead vehicle from upstream node at end of time step; and
s_f = distance of following vehicle from upstream node at beginning of time step.

This expression is derived under the assumption that a "normal" deceleration is 7 ft/sec^2; the application of this value and assignment of $\Delta t = 1$ account for the apparent inconsistency in units. No attempt was made to validate this expression rigorously; detailed testing uncovered no instabilities in vehicle trajectories and indicated realistic vehicle headways.

In the following sketch,

s_ℓ^T = distance traveled by the lead vehicle during deceleration at 10.5 ft/sec^2 (50 percent above "normal") to a stopped position; and
s_f^T = distance traveled by following vehicle during deceleration at 7 ft/sec^2 to a stopped position.

The model seeks the value of acceleration (or deceleration) that the following vehicle must now (at the beginning of the time step) apply to prevent a collision with the lead vehicle, if the latter should begin to decelerate at 10.5 ft/sec^2 to a stop. The following vehicle's deceleration, if this event should occur, would be normal, i.e., 7 ft/sec^2. The rationale is that a driver anticipates a sudden deceleration (50 percent above normal) and maintains his speed and spacing appropriately to prevent a collision. This



scenario may be written mathematically (in the limiting case of near collision) as

$$s_f^T = s_\ell + s_\ell^T - s_f - \Delta s_f - L_\ell \tag{2}$$

Writing

$s_\ell^T = V_\ell^2/2d_\ell = V_\ell^2/21,$

$s_f^T = V_f^2/14,$

$V_f = V_{fi} + \Delta V,$

$V_f^2 \to V_{fi}^2 + 2V_{fi}\,\Delta V,$

$\Delta s_f \to \frac{1}{2}(V_{fi} + V_f)\,\Delta t,$

$V = a_f \cdot \Delta t,$

$\Delta t = 1,$

and substituting appropriately into Eq. 2 yield

$$(V_{fi}^2 + 2V_{fi}a_f)/14 = s_\ell + (V_\ell^2/21) - s_f - [V_{fi} + (a_f/2)] - L_\ell$$

Solving for a_f yields the expression shown above ($7/2$ rounded to 3).

QUEUE DISCHARGE

Each vehicle at the head of a queue prior to the onset of green is stochastically assigned a start-up delay that must be exhausted after the green phase is activated and before it is discharged. Each following vehicle in the queue is stochastically assigned a discharge headway that is related to the specified mean headway value, the statistical distribution about that mean, and its original position in the queue. When a vehicle is discharged, the remaining members of the queue move up in response to a "green wave" propagating upstream at a speed of 1 vehicle (≈20 ft) per sec. Hence, the ninth vehicle in a queue when the green phase is activated remains motionless for 8 sec after the first vehicle discharges.

Left-turn movements represent a critical component of design. For unprotected phases, a left-turn vehicle first in queue may "jump the gun" before oncoming traffic (determined probabalistically), seek an acceptable gap in the oncoming traffic (also determined probabalistically), or negotiate the turn during the following amber signal. A multitude of tests are made for each vehicle ready to discharge, depending on its intended maneuver, type, status of traffic on receiving link, its lane assignment in that link, and many other factors.

BUS TRAFFIC

It is well recognized that, although urban bus vehicles constitute a relatively small percentage of total traffic, their impact on general operations is profound. The need for buses to maneuver at stations, the blockage effect of buses dwelling at stations, their size, and their sluggish operating characteristics, all contribute to degrading overall traffic performance. Considerable effort was expended to ensure that bus traffic was explicitly and realistically treated by the model. Vehicles, identified as buses in the sense of vehicle length and acceleration characteristics, traverse prescribed paths (routes) through the network servicing those stations assigned to that route. The probability of stopping and the duration of dwell are assigned to each vehicle stochastically. Impedance with other traffic, queuing that prevents buses from accessing their stations, possibility of station storage being saturated, and many similar factors are rigorously modeled. Separate sets of statistics are accumulated and displayed for bus traffic.

RESPONSIVE SIGNAL CONTROL

The model was designed for the express purpose of evaluating responsive signal control policies. To this end, the ability of the model to identify the status of each vehicle—lane position, location, speed, type, and intended maneuver—provides it with the means of replicating almost any control policy, either local (intersection-specific) or global (system-wide). Such policies may be introduced into the model, through the medium of additional FORTRAN code, with no interface problems whatever. This is achieved by providing as many as 9 "windows" in the code that permit the addition of subroutines to reflect these policies. Each subroutine, representing a particular policy, may refer to one or more specified intersections of the network. In addition, a computer-monitored control system, responding to signals accessed by detectors as determined by the surveillance simulation (another optional component of the model), can be rigorously simulated by UTCS-1 to predict its overall performance prior to implementation.

REFERENCE

1. Bruggeman, J., Lieberman, E., and Worrall, R., Network Flow Simulation for Urban Traffic Control System. KLD Assoc., Inc., Tech. Rept. FH-11-7462-2, 1971.