Review of Road Traffic Network Simulation Models

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Proposals for computer traffic simulation date from 1951, and the first actual documented simulation was performed in 1955 on an analog computer. Since that time, many simulation models have been developed as knowledge of traffic principles has increased and computer facilities have improved. Such traffic simulation models may be placed in three groups: single road, single intersection, and traffic network. This paper discusses only the last. Nineteen network simulation models are discussed. These are grouped into ten obsolete models, six traffic network models suitable for current computers, and the simulation portions of three signal optimization programs. A brief description of the operating principles and unique features of each model is given, and the level of modeling detail, model flexibility, and usefulness of the output are assessed. Validation efforts on the model are considered, and, where known, computer language, type of machine, core requirements, and speed of execution are given.

There are three classes of traffic simulation models: single road, single intersection, and network. Hsu and Munjal (2) have reviewed the single road freeway models, but rural road models, which reproduce the effects of sight distance restrictions, rolling terrain, and passing opportunities, are rare. Single intersection models have generally been built for a specific purpose and are not usually available as a consumer product. This paper discusses the currently available network simulation models and some now obsolete network models. We also summarize three signal optimization programs that include traffic network simulation.

Modern traffic simulation programs use digital computers and time-oriented bookkeeping; the event-oriented bookkeeping associated with most simulation languages seems inappropriate.

Some models (macroscopic) treat the traffic stream as a continuum and conceptualize the traffic stream as a fluid. Individual vehicles are not identified in macroscopic models; indeed, a network element may even contain fractional vehicles. Macroscopic models generally are very economical of computer storage and very fast in execution, because they do not have to keep track of each vehicle. However, they cannot represent the traffic stream in the detail that many traffic engineers want.

Platoon models are a half-step toward detailed realism. In these models, vehicles are grouped into platoons, and the program keeps track of the location, speed, acceleration, and size of the platoon. Platoon speed, usually a function only of the general density of vehicles in the vicinity of the platoon, avoids complicated car-following calculations.

Microscopic simulation models are the ultimate in detailed treatment. Each vehicle is identified and its position, speed, acceleration, and other characteristics are stored. Microscopic models deal with two separate areas: streets and intersections. On streets, vehicle behavior is usually approximated by controlling one vehicle's speed by the preceding vehicle (car following). Car-following rules can be quite complex. Queuing behavior and the delay in accelerating away from the head of the queue are usually treated in detail; there are indications that this can be a critical factor in the accuracy of simulation, at least for urban networks. Lane changing may or may not be allowed, and other details of street traffic can be represented. Buses and trucks can also be handled separately.

Intersection behavior is considerably more complex and difficult to model. Problems of pedestrian interference, turning radii, and collision avoidance all must be faced. Usually these problems are treated superficially; for example, random delay is assigned for pedestrian interference. Because one primary function of network models is to evaluate signal control strategies, traffic signals are usually modeled in considerable detail.

The various simulation models (see Table 1) discussed here should be assumed, unless specifically indicated otherwise, to have the following characteristics. They are fully microscopic, meaning that the model stores a specific location, speed, and acceleration for each individual vehicle. Moreover, the vehicles engage in car following; that is, the speed of a vehicle is determined in some reasonable, predetermined manner by the speed of any vehicle directly in front of it. If there is no vehicle in front, it travels at its "desired" speed. Vehicles obey traffic signals and stop and yield signs.

All variables in the system (vehicle locations, speeds, accelerations, and signal indications) are updated once each time step, which is a user-specified constant, often 1 s. The computer program is written in FORTRAN. The simulation starts collecting data only after some initial period, which starts with the system empty and ends when some test for equilibrium is satisfied.

Vehicle routes are determined from origin-destination tables (O-D) or the probability of turning left, through, or right at the end of each link (turning movements).

OBSOLETE MODELS

The *DISCRETE AND CONTINUOUS VARIABLE SIMULATION MODEL*, developed by Matthewson, Trautman, and Gerlough, was perhaps the first traffic simulation model to actually be constructed (3, 4). It represented a signalized intersection network with one lane in each direction and pedestrians who delayed turning traffic. Validation was primarily by reasonableness. The model was based on an analog rather than a digital computer and therefore had to be rebuilt for each new intersection or network.

The *STARK/NBS MODEL*, produced by Stark of the National Bureau of Standards for the IBM 704 computer (5), achieved realism through the use of fairly detailed traffic behavior rules. The model included traffic signals, stop signs, one- and two-way streets, and oblique intersections within the program structure. Documentation for this model is hard to obtain and would not be sufficient to recreate it for use on another computer. The model provided complete statistics on vehicle behavior. The most interesting output was a movie of the simulation, which was the only verification of the realism of the model.

A simulation model was developed by Francis and Lott for the *ROAD RESEARCH LABORATORY* to examine proposed changes in traffic signal patterns in central London (6). This program had a moderate level of detail but did not distinguish between different types of

Table 1. Characteristics of network traffic simulation programs.

Model	Type	Time Step	No. of Vehicle Types	Route Selection	Language, Machine	Time Compression	Remarks
Discrete and continuous variable	Analog	Continuous	1	—	Hardwired machine	1:1	Electronic elements: one-to-one correspondence with network
Stark/NBS	Micro	¼ s	3	Fixed during vehicle generation	Assembly, IBM 704	15:1 (9 nodes)	First to use cartoon movie graphics as output medium
Road Research Laboratory	Micro	1 s	1	Turn ∢	Assembly, Ferranti Pegasus	2:1 (36 links, 9 nodes)	0, 1 representation of vehicle location
Australian or Pak-Poy	Micro	—	1	Turn ∢	IBM 1620 and 7090	2000:1 (1 node, 4 links) IBM 7090	
VTS	Micro	Event oriented	1	Turn ∢	GPSS, IBM 7090	1:1 (10 nodes) 1:3.5 (25 nodes)	
TRANS	Short platoons	2 s	1	Turn ∢	Assembly, IBM 709	20:1 (36 links, 9 nodes)	Trucks diffused uniformly through traffic
Hartley	Hardware	⅓ s	1	Fixed	Atlas traffic simulator	NA	
Birmingham	Micro	—	4	Fixed routes	EGTRAN 3, ICL	4:1 (3 nodes)	
DYNET	Micro	1 s	2	Turn ∢	FORTRAN, IBM 360	5-10:1 (46 links, 21 nodes)	
Sakai and Nagao	Large platoons	4 s	—	Turn ∢	NA	Very fast	All vehicles in a 50-m segment act as platoon
VETRAS	Micro	Event oriented	1	Turn ∢	GPSS, IBM 360/370	Slow	
VPT	Micro	Variable (1 s)	3	Turn ∢	FORTRAN and COMPASS, CDC 7600	Very slow (1:1 or slower)	Very detailed
UTCS-1	Micro	1 s	3	Turn ∢	FORTRAN, IBM 360, CDC 7600	2.5:1 (26 links, 12 nodes)	
SCOT	Platoon	Variable (6 s)	3				
SIGNET	Micro	Variable (1-s multiples)	2	Turn ∢	FORTRAN IV, CDC 6500	6.5:1	Traffic signals only, no stop or yield
Microassignment	Macro	Static	1	O-D	FORTRAN and Assembly, IBM 360	5:1 (1334 links)	
CORQ	Macro	Static	1	O-D	FORTRAN, IBM 360	30:1 (125 links, 65 nodes)	Carries excess demand over to next assignment
TRANSYT	Macro	Static	5	Turn ∢	FORTRAN	Very fast	Single-pass calculation of pulse shapes
SIGOP II	Macro	Static	1	Turn ∢	FORTRAN	Function of number of iterations desired	User-selected, multiple-pass calculation of pulse shapes
CORQ1C	Macro	Static	2	Both	FORTRAN, CDC	Very fast	Can generate O-D

vehicles or follow them through the network. Each lane was divided into short sections that corresponded to a computer storage "bit." For each occupied section, a "one" would be registered in the storage location. Ones moved from bit to bit in the computer memory to represent vehicle motion. This model simulated only signalized intersections of three or four legs. However, separate specification of right- and left-turning volumes and signal offsets and phasing was possible. Output included total time simulated, volumes and delays by link, average delays and average queues by link, and maximum queues by link. The maximum network size was 30 intersections, 80 links, and 20 peripheral arms. The program was executed at approximately 18/n times real time, where n was the number of intersections.

The *AUSTRALIAN OR PAK-POY MODEL* (7) was written to analyze traffic signal controllers and intersection capacity and was reasonably flexible. Validation was limited and consisted primarily of comparison of model results with before-and-after field studies of intersections. Documentation is unavailable. The primary outputs of the model were delay, queue length, and degree of saturation.

VEHICLE TRAFFIC SIMULATOR (VTS) was constructed by A. H. Blum (8, 9) and used general purpose simulation system (GPSS) language intersection modules assembled to form a network. The level of detail in VTS was good; the model simulated traffic signals and special sources and sinks of traffic. Fixed time signals were assumed to control all intersections, and the car-following logic was "change lane or assume speed of leading vehicle." Vehicles were not identified by type, but different types could be approximated by assigning vehicle characteristics. No validation was performed on this model and documentation is limited to one article (8).

The *TRANS* (simply a name) *MODEL* developed by Gerlough, Wagner, Rudder, and Katz, was the first network simulation model to enjoy wide usage and validation. At least four versions were produced from 1962 to 1968 (10, 11, 12, 13, 14). Although TRANS is now obsolete, it led to several other models (see the DYNET, SIGNET, and UTCS-1 models below). The level of detail in the TRANS model was moderate. Automobiles were grouped into short platoons. Vehicles could switch lanes instantaneously if they were queued behind left-turning vehicles. Vehicle behavior at signals was quite detailed. Different models of TRANS used different time steps; version 4 had a user-specified updated period that could not be less than 2 s. The TRANS model was the first to be widely validated, and validation runs were made in Washington, D.C., Los Angeles, and Detroit. The documentation explained fairly clearly how to prepare input data, but documentation of program logic was scanty. Data preparation was tedious, because many parameters had to be supplied. Output gave the usual traffic parameters both link by link and networkwide.

HARTLEY, in England, developed a basic model utilizing a special purpose computer identified as the Atlas Digital Traffic Simulator. A diffuser was used to link intersections and replicate platoon behavior, while a random pulse generator created input traffic. Because of its fixed program, the model was relatively easy to run but had very limited flexibility. Validation was by sensitivity analysis and reasonableness. Documentation was limited to two articles and a doctoral dissertation (15, 16, 17).

The *BIRMINGHAM MODEL*, also developed in England, by Storey (18), handled four categories of vehicles. Car-following logic was limited, and vehicles were assigned to their lanes based on their turning movement at the subsequent intersection. An unusual feature of this model was the assignment, to avoid path looping, of complete vehicle routes from entry through the network. The model could represent both fixed-time and vehicle-actuated signals. Output was limited to printouts of vehicle location within the network and both journey times and delays for each route. Although the model was not validated, sensitivity testing indicated that it produced reasonable variations in output values based on input changes.

The *DYNAMIC NETWORK ANALYSIS OF URBAN TRAFFIC FLOW (DYNET) SIMULATION MODEL* was developed by Lieberman of General Applied Science Laboratories (GASL) in 1969 (19). It was based on the TRANS model, used many of its features, and made numerous specific improvements. Particular effort was expended on making the model fully microscopic and simplifying the input requirements. Trucks and automobiles were represented separately and were generated according to a shifted exponential distribution. A vehicle was assigned a lane when it first entered a link according to the turn the vehicle expected to make when it exited from that link. A vehicle could change lanes when it entered a queue if the queue in the adjoining lane were shorter and the turning movement permissible from the new lane; the vehicle would change lanes only if an acceptable gap were available. Left-turning vehicles examined the oncoming traffic and remained in queue until a suitable gap appeared. At stop signs and signals vehicles behaved very much as they did in the TRANS model. Its detailed microscopic character and the shorter time step generally used (1 s) made the DYNET model actually run more slowly than the TRANS model. If the time steps had been the same in both models, speed of execution would have been comparable.

SAKAI AND NAGAO of Japan developed a simple platoon macroscopic model (20). In this model, roadways were partitioned into 50-m segments. The computer kept track of the number of vehicles in these segments, and the average speed of these vehicles was a function of number of vehicles in the segment. Buses and trucks were replaced by their equivalent number of passenger automobiles.

CURRENT MODELS

VEHICLE TRAFFIC SIMULATION MODEL (VETRAS) (21) by IBM builds on Blum's earlier VTS model; it is somewhat more refined and detailed than models built from scratch. The logic includes provision for right turn on red, and car-following logic is "switch lanes or assume speed of leader car." The model allows easy modification of control logic, and its modular structure and input format make it easy to set up a variety of networks. Network flexibility is limited by a restriction to four-legged intersections. A variety of vehicle characteristics can be generated, but the addition of trucks and buses as distinct entities would require minor programming changes to produce separate statistics. Documentation for VETRAS is not extensive but is clear and does include flow charts. Validation was limited to sensitivity testing.

VEHICLE PERFORMANCE IN TRAFFIC (VPT) MODEL developed by the Aerospace Corporation is an exceptionally detailed, totally microscopic network model (22, 23, 24). Automobiles, trucks, and buses are generated according to a Poisson distribution. In addition to the individual vehicles, the characteristics of the drivers are generated stochastically and include desired speed, desired lane, gap acceptance characteristics, and a frustration factor that determines how long a driver will tolerate following a slower driver. These characteristics are correlated so that a reckless driver generally has the characteristics associated with that description. Vehicles follow each other according to a reasonable car-following law based on the apparent rate of change of the visual angle subtended by the leading vehicle. Lane changing is more complex in this model than in any other; a driver can change lanes simply because he is tired of following a slower driver. This is the only simulation program that includes "actual" accidents. When two vehicles merge into the same spot, they are considered disabled and remain parked in that spot throughout the simulation. Flexibility of this model is somewhat restricted because surface streets are assumed to intersect at right angles only. Also, there are some restrictions on traffic signal displays that make these representations less flexible than those found elsewhere. The model does not consider pedestrian interference. Validation of this model is poor; it has given reasonable results in one or two small tests. User documentation is not generally available. Input requirements are quite extensive because of the detailed microscopic nature of the model. The user may choose the desired output from a wide variety of traffic-related measures such as average speed, average delay, fuel consumption, and vehicle emissions.

URBAN TRAFFIC CONTROL SYSTEM (UTCS-1) AND SIMULATION OF CORRIDOR TRAFFIC (SCOT) are closely related models. UTCS-1 was developed by Peat, Marwick, Mitchell and Company and GASL, while SCOT was produced by GASL alone. UTCS-1 was designed to evaluate traffic signal systems (25, 26). It is based on the DYNET model and is fully microscopic; vehicle data are stored in packed words. The packing operations are done in the program where the information is used or produced. Initialization continues until the number of vehicles in the system appears constant. The time step is fixed at 1 s. SCOT is identical to UTCS-1 except that the Dynamic Analysis of Freeway Traffic (DAFT) model has been included (27). On freeways, vehicles are grouped into platoons; individual statistics are not kept for each vehicle. The update period on the freeway is variable but is usually about 6 s. Level of detail in the UTCS-1 model is excellent. Pedestrian interference is represented, and the lane-changing rules are reasonable. Oncoming traffic interferes with left turns as does traffic that is backed up from the preceding intersection. The freeway portion of SCOT is less realistic. The speed rule as a function of density is somewhat arbitrary, and platoons have an inherent lack of realism. Validation of these models is moderately good. UTCS-1 was extensively validated in Washington, D.C., and the freeway portion of SCOT was briefly evaluated in Dallas. UTCS-1 has been widely used and is generally accepted as giving reasonable results. Documentation is hard to follow but is complete and readily available. The detailed character of the required data makes input preparation difficult and time consuming. The SCOT freeway data are particularly awkward in that two parameters determined by a separate computer program are required. Output is full and complete both link by link and systemwide. A new version of UTCS-1 gives emissions and fuel consumption.

The *SIGNET* (a signal network optimization system) model (28, 29) was developed by Davies as a master's thesis at Purdue University. Input to SIGNET is fairly complex. Output statistics include total vehicle miles, total delay, average delay, delay standard deviation, and average speed. The program will accommodate up to 85 links without modification of dimension statements. SIGNET borrows heavily from the TRANS model but is fully microscopic and utilizes computer words to describe vehicles in a manner similar to UTCS-1. Stop and yield sign control is not represented. However, the model is fairly flexible in terms of intersection geometries and traffic controllers. Model validation was extremely limited and merely confirmed that the simulation outputs were reasonable and consistent with travel time studies. The documentation consists of a very thorough master's thesis project report that includes subroutine descriptions and flow charts.

MICROASSIGNMENT (30, 31, 32), by Creighton, Hamburg, Inc., is a traffic assignment tool developed for transportation planning purposes; it was not designed as a traffic simulation program. However, microassignment considers origins and destinations on a block-by-block basis and therefore has many of the features normally associated with a simulation model. Basically, it was designed to give the expected traffic on any street for a given O-D pattern, but it also outputs the average speed and delay on each link. Microassignment is very macroscopic (for a simulation model) and ignores many of the fine details critical to traffic engineering. Its treatment of traffic signals includes only the coarsest representation of phasing and ignores the effects of signal offsets altogether. The key to the operation of microassignment is in the novel link-node structure. Nodes are placed in the center of each block so that a left-turning vehicle travels on a totally different link from one traveling straight through the intersection. In this way, each link can be assigned a fairly accurate value for the delay associated with the corresponding movement. These delays reflect the character of the control at the intersection (for example, a left-turn link has a lower delay if there is a protected left-turn phase) and, possibly, the traffic on opposing links. For any given O-D pattern, microassignment computes the minimum path and then assigns all the traffic from a batch of origins to their destinations based on minimum time. A new minimum time is then computed, and another batch of trips is assigned. The batch size can be specified by the user; usually, to achieve maximum accuracy, only one path is loaded at a time. Because of its macroscopic character, microassignment can rapidly handle very large networks of even 1000 city blocks. The assignments are essentially static, and a time compression ratio is not directly pertinent. A network of 1334 links took from 108 to 365 s (depending on the batch size) to do one complete assignment. If new assignments are required every 15 min, this corresponds to a time compression of 2.5:1 to 9:1.

CORQ for traffic assignment with queuing in corridors) is a new traffic simulation model written by Yagar of the University of Waterloo (33). It has many features of microassignment. Given a set of O-D tables for, say, successive 15-min periods, it calculates the traffic assignments for one period. It uses a conventional link-node representation of the network and represents signals as capacity restrictions only. The unique feature of this model is that, when capacity cannot accommodate demand, the excess vehicles are stored on the link and added to the demand for the next period. One may visualize the flow as a fluid leaking through the network. User documentation is not yet available for CORQ.

SIGNAL OPTIMIZATION PROGRAMS

TRANSYT (simply a name) was developed by Robertson of the U.K. Transport and Road Research Laboratory as a signal optimization program (34, 35, 36, 37, 38) and, therefore, lies outside the primary emphasis of this paper. However, it contains, as an integral element, a simulation program that can be used without the optimization feature. The logic of the TRANSYT simulation program is deceptively simple. The program is totally macroscopic and completely deterministic; no random numbers are used at all. Uniform vehicular flow enters the upstream end of the farthest upstream link of the network. The flow arrives at the link's downstream end, where it accumulates during the red phase. When the signal turns green, vehicles discharge at the capacity rate of the signal until the queue is dissipated; thereafter the vehicles discharge at the rate at which they arrive. This emergent platoon of vehicles now has a specific shape and arrives at the next downstream stop line with a delay appropriate to the length of the link and to the speed of progression on the link. To enhance realism, the shape of the platoon is changed slightly to reflect dispersion. Again, the discharge from the signal is at intersection capacity until the queue is discharged. In this way, the shape of the platoons at any intersection reflects the effects of all the upstream intersections. Provisions are made for turning vehicles and for the arrival of vehicles at the stop line from the secondary flows that have turned onto the link. Thus TRANSYT is able to represent the performance of the network in a single pass without any initialization. Input preparation is comparatively simple and easy, but output, primarily delays and stops, is not as detailed as that of most models.

SIGNAL OPTIMIZATION (SIGOP II) (39, 40, 41), developed by Lieberman and Woo, is a descendant of TRANSYT and SIGOP I (SIGOP I is an optimization program now obsolete and contains nothing relevant to the subject of this paper) and, like them, is a signal optimization program. Like TRANSYT, it contains a macroscopic traffic flow model that can be used to evaluate the stops and delays of an existing signal system. The logic of SIGOP II utilizes dynamic programming techniques. SIGOP II orders the traffic flows into nine primary and secondary platoon combinations according to when the platoon departs from the first intersection and when it arrives at the second. Modification of platoon characteristics depends on the length of the link and the speed of progression on the link. Provision is made for turning movements and turn pockets. One evolutionary step in SIGOP II is its ability to model the effects of multiphase signals. Input preparation is fairly straightforward once the notation for describing multiphase signals has been mastered. Special coding sheets and a fully documented case study are included with the documentation. Output includes time-space plots of signal control along specified arterials as well as link-by-link statistics. SIGOP II is still being field tested by the Federal Highway Administration and, therefore, is currently available only on an experimental basis.

CORQ1C is a corridor optimization program for queuing (42, 43). As such, the range of networks that can be analyzed is restricted; the program explicitly assumes a one-directional freeway and a parallel arterial with two-way connecting streets. The freeway part of the program is FREQ3C (44), which was developed by May and his coworkers at the University of California. The surface street portion is the TRANSYT program discussed above. Both optimization programs contain simulation programs as subsets. If simple simulation is desired, the network geometry can be considerably more general than that assumed for optimization. Both models have been well validated.

REFERENCES

1. H. H. Goode. Simulation: Its Place in Systems Design. Proc., Institute of Radio Engineers, Vol. 39, No. 12, Dec. 1951, pp. 1501-1506.
2. Y. S. Hsu and P. K. Munjal. Freeway Digital Simulation Models. TRB, Transportation Research Record 509, 1974, pp. 29-41.
3. J. K. Matthewson, D. L. Trautman, and D. L. Gerlough. Study of Traffic Flow by Simulation. Proc., HRB, Vol. 34, 1955, pp. 522-529.
4. J. H. Matthewson and others. Analysis and Simulation of Vehicular Traffic Flow. ITTE, Univ. of California, Los Angeles, Rept. 20, Dec. 1954.
5. M. C. Stark. Computer Simulation of Street Traffic. National Bureau of Standards, Technical Note 119, Nov. 1961.
6. J. G. F. Francis and R. S. Lott. A Simulation Programme for Linked Traffic Signals. Proc., 2nd International Symposium on Theory of Road Traffic Flow, London, 1963, OECD, Paris, 1965, pp. 257-259.
7. M. G. Grace, R. W. J. Morris, and P. G. Pak-Poy. Some Aspects of Intersection Capacity and Traffic Signal Control by Computer Simulation. Proc., Australian Road Research Board, 1964, pp. 274-304.
8. A. M. Blum. A General Purpose Simulator and Examples of Its Application: Part III—Digital Simulation of Urban Traffic. IBM Systems Journal, Vol. 3, No. 1, Nov. 1, 1964, pp. 41-50.
9. A. M. Blum. Vehicle Traffic Simulator Program. SHARE General Program Library 7090/IBM/0027, International Business Machines Corp., Yorktown Heights, N.Y., Aug. 1965.
10. D. L. Gerlough, F. A. Wagner, Jr., J. B. Rudden, and J. H. Katz. A Traffic Simulation Program for a Portion of the Traffic System in the District of Columbia. District of Columbia Department of Highways and Traffic; U.S. Bureau of Public Roads, 1963.
11. F. A. Wagner, Jr., F. C. Barnes, D. P. Stirling, and D. L. Gerlough. Urban Arterial and Network Simulation. Planning Research Corp., Los Angeles, Rept. PRC R-926, Dec. 1966.
12. D. L. Gerlough and F. A. Wagner, Jr. Improved Criteria For Traffic Signals and Individual Intersections. NCHRP, Rept. 32, 1967.
13. F. A. Wagner, Jr., F. C. Barnes, and D. L. Gerlough. Refinement and Testing of Urban Arterial and Network Simulation. Planning Research Corp., Los Angeles, Rept. PRC R-1064, Nov. 1967.
14. F. A. Wagner, Jr., and F. C. Barnes. Traffic Simulation Case Study: City of Detroit New Center Area Network. Planning Research Corp., Los Angeles, Rept. PRC R-1064B, April 1968.
15. M. G. Hartley and S. I. Saleeb. Simulation of Traffic Behavior Through a Linked Pair of Intersections. Transportation Science, Vol. 2, 1968, pp. 51-61.
16. M. G. Hartley and D. H. Green. Study of Intersection Problems by Simulation on a Special Purpose Computer. Traffic Engineering and Control, Vol. 7, No. 3, July 1965, pp. 219-223.
17. S. I. Saleeb. Logical Design and Associated Computer Studies for the Hardware Simulation of Traffic Dispersion. Manchester Univ., England, PhD thesis, 1967.
18. C. E. Storey. Simulation of Traffic by Digital Computer. Traffic Engineering and Control, Vol. 2, No. 10, Feb. 1970, pp. 464-467.
19. E. Lieberman. DYNET: Dynamic Network Analysis of Urban Traffic Flow. General Applied Science Laboratories, Westbury, Conn., Rept. TR-718, April 1969.
20. T. Sakai and M. Nagao. Simulation of Traffic Flows in a Network. Communications of the ACM, Vol. 12, No. 6, June 1969, pp. 311-318.
21. IBM Traffic Signal Control Systems Simulators. Federal Systems Center, International Business Machines Corp., Gaithersburg, Md.
22. P. H. Young and H. S. Porjes. Surface Street Simulation Using the FREEWAY Program. Aerospace Corp., El Segundo, Calif., Rept. ATR-76 (9320)-2, Oct. 31, 1975.
23. H. S. Porjes, C. Speisman, and P. H. Young. An Advanced Computer Program for Determining Vehicle Emissions and Fuel Economy Under Road Traffic Conditions. Proc., 4th Transpo LA—Economic Leverage for Tomorrow, Western Periodicals Co., North Hollywood, Calif., Nov. 1975, pp. 242-251.
24. G. W. Harju, L. R. Bush, R. F. Kramer, and H. S. Porjes. An Advanced Computer Concept for Freeway Traffic Flow Modeling. Proc., Summer Computer Simulation Conference, Simulations Councils, La Jolla, Calif., June 1972.
25. E. B. Lieberman, R. D. Worrall, and J. M. Bruggeman. Logical Design and Demonstration of the UTCS-1 Network Simulation Model. HRB, Highway Research Record 409, 1972, pp. 46-56.
26. Network Flow Simulation for Urban Traffic Control System: Phase II. Peat, Marwick, Mitchell and Co., 1973, 5 vols.; NTIS, Springfield, Va., PB 230 760-230 764.
27. P. Ross, ed. SCOT Model, User's Manual and Program Documentation. Traffic Systems Division, Office of Research, Federal Highway Administration, Working Document, May 1975.
28. G. W. Davies, W. L. Grecco, and K. W. Heathington. A Generalized Street Network Simulation Model. TRB, Transportation Research Record 509, 1974, pp. 16-28.
29. G. W. Davies. Optimization of a Traffic Signal System Through Computer Simulation. Joint Highway Research Project, Engineering Experiment Station, Purdue Univ., Lafayette, Ind., Project C-36-17JJ, No. 8-4-36, June 22, 1972.
30. G. J. Brown and R. S. Scott. Micro-Assignment: A New Tool for Small Area Planning. HRB, Highway Research Record 322, 1970, pp. 149-161.
31. Micro-Assignment. Creighton, Hamburg, Inc.,

Delmar, N.Y., Final Rept., 1969; U.S. Bureau of Public Roads.
32. Adaption and Calibration of Micro-Assignment to the Golden Triangle Area of Pittsburgh. Creighton, Hamburg, Inc., Bethesda, Md., Feb. 1973.
33. S. Yagar. CORQ: A Model for Predicting Flows and Queues in a Road Corridor. TRB, Transportation Research Record 533, 1975, pp. 77-87.
34. F. A. Wagner, Jr. TRANSYT Method for Network Optimization. Proc., 42nd Annual Meeting of Institute of Traffic Engineers, New York, Sept. 26, 1972.
35. D. I. Robertson. TRANSYT: A Traffic Network Study Tool. British Road Research Laboratory, Crowthorne, England, Rept. BRRL 253, 1969.
36. D. I. Robertson. TRANSYT Method for Area Traffic Control. Traffic Engineering and Control, Vol. 2, No. 6, Oct. 1969, pp. 276-281.
37. D. I. Robertson. TRANSYT: Traffic Study Tool. Proc., 4th International Symposium on the Theory of Traffic Flow, Karlsruhe, Beiträge zur Theorie des Verkehrsflusses, Herausgegeben von Bundesminister fur Verkehr, ADT, Bonn, 1968, pp. 134-144.
38. D. I. Robertson. User Guide to TRANSYT Version 5. U.K. Transport and Road Research Laboratory, Crowthorne, England, Technical Note TN 813, March 1973.
39. F. A. Wagner, Jr. SIGOP/TRANSYT Evaluation: San Jose, California. Federal Highway Administration, Rept. FH-11-7822, July 1972.
40. SIGOP: Traffic Signal Optimization Program, User's Manual. Peat, Marwick, Livingstone and Co., 1968; U.S. Bureau of Public Roads; NTIS, Springfield, Va., PB 182 835.
41. SIGOP: Traffic Signal Optimization Program, Field Tests and Sensitivity Studies. Peat, Marwick, Livingstone and Co., 1968; U.S. Bureau of Public Roads; NTIS, Springfield, Va., PB 182 836.
42. M. P. Orthlieb and A. D. May. Freeway Operations Study: Phase IV—Freeway Corridor Control Strategies. ITTE, Univ. of California, Berkeley, Rept. 74-5, June 1975.
43. A. D. May and M. P. Orthlieb. An Urban Freeway Corridor Control Model. TRB, Transportation Research Record 601, abridgment, 1976, pp. 8-9.
44. Y. Makigami, L. Woodie, and A. D. May. Bay Area Freeway Operations Study: Part I—The Freeway Model. ITTE, Univ. of California, Berkeley, Final Rept., 1970.

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Simulation of Bus Lane Operations in Downtown Areas

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An investigation of potential operational capacities of downtown bus lanes was carried out in Ottawa, Canada. The results could improve coordination between bus priority treatments within downtown areas and those on the major transit corridors feeding the downtown areas. This paper describes the simulation model that was developed during the course of the study to simulate bus behavior in a downtown bus lane. Several operating strategies were tested and evaluated. Depending on the strategy selected, a bus flow rate of 150 to 170 buses/h can be achieved. This flow rate can accommodate 8000 to 9000 passengers/h with acceptable loading standards, operating speeds, and existing standard equipment. Further tests and research are suggested.

Bus priority systems, introduced in many cities, may utilize different measures from the groups listed below:

1. Freeway related measures: reserved lanes, separate roadways, exclusive ramps, queue jumping, metered ramps, and bypass of toll barriers;
2. Arterial related measures: reserved lanes with-flow or contra-flow, separate roadways (bus-only streets), special signalization, special turn permission, and pulling away priority at bus stops;
3. Busway measure: exclusive bus-only roadway either grade separated or with at-grade intersections; and
4. Terminal measure: off-street loading, unloading, and short-term storage of buses, usually connected to freeways or arterials with bus priority measures.

Coordination of the operational capabilities of these various measures could lead to an improved level of service and more efficient use of buses during peak periods. For example, if downtown bus lanes can accommodate the large number of buses arriving from reserved freeway lanes from suburban areas, overall travel times can be reduced.

Generally accepted minimum installation criteria for bus lanes are 30 to 90 buses/h (4); maximum operating capacities of downtown bus lanes are currently 90 to 120 buses/h. These are sometimes exceeded, as in Ottawa, where flows in excess of 140 buses/h occur in some bus lanes.

The success of bus transit in this context relies on how far into the future a municipality's improved bus-based system can meet peak-hour transit needs in major demand areas. The capacity limits of a bus-based system will probably be experienced in the downtown collection and distribution system rather than on reserved freeway lanes and busways between downtown and suburban areas. Because bus lane volumes in Ottawa are already as high as any that have ever occurred in the transit industry's experience, a study was commissioned to investigate the operating capacities of bus lanes in a downtown environment.

After briefly reviewing the literature and summarizing field experiments, this paper will describe the simulation model we developed during the course of the project. A number of bus operating strategies were tested and