the before system. This example demonstrates a present limitation of the model.

DISCUSSION OF RESULTS

The technique developed for using the model is a simple before and after comparison of alternatives. Selecting MOEs for comparison is determined by the application. There are a few precautions that must be observed:

1. Be sure the simulated system adequately represents the alternative being studied.
2. Examine simulated results in detail using link statistics. Look for queue locations.
3. Make sure simulated signal systems are operating as designed. Use the output feature of frequent printouts to check the status of signal phases.
4. When comparing before and after simulated results, use the same input volumes. There will probably be times when observed volumes may be used, but if so be cautious in making comparisons.
5. Remember simulation is not the real world. Apply all results by using good judgment that comes from experience. If results look unreasonable, do not use them.

SUMMARY AND CONCLUSIONS

The NETSIM model has been used extensively to evaluate traffic control strategies for single intersections, arterials, and grid networks. Pedestrian control problems have been analyzed, bus system plans have been studied, and fuel consumption and emissions analyses have been applied to a variety of systems. Economic analysis has proved useful in many studies as well as for decision making in design projects.

More recently, coordination of actuated signal systems on arterials has been attempted with some success. Planning studies are presently under way.

NETSIM has been applied to a fairly wide variety of problems with satisfactory results, but how accurate these results are is likely to be the most frequently asked question. It must be remembered that all the results and values (MOEs) derived from simulation are not precise field measurements. Simulation is a means of making reasonable approximations of operating control systems for comparison purposes. Our experience is that these approximations are useful and generally within accuracy limits in measuring traffic flow (daily and monthly variations, etc.). It provides a means to analyze problems that are difficult or impractical to approach by any other means. Results have been used for decision making in numerous problems, and no real failures have been experienced. NETSIM has been well supported by FHWA, and its continued support is urged. Capability to simulated, more advanced control technology is recommended. Plans are under way for some of these. Simulation of computer-controlled systems would be a desirable goal. This capability would help avoid costly and embarrassing errors in the design of those systems.

NETSIM is a very useful tool. It is highly recommended for solving a wide variety of control problems.

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Traffic Flow Simulation: User Experience in Research

Jamie W. Hurley, Jr., and Ahmed E. Radwan

Traffic simulation computer programs have long been viewed as practical and effective tools for analyzing traffic flows, especially when one considers the expense and time required to collect and analyze field data. In addition to being used for operational purposes, some of these programs, especially those based on microscopic flow simulation, have been used for research. This paper describes experiences encountered while using traffic simulation for research at Virginia Polytechnic Institute and State University (VPI). Because of its scope and considerable potential as a research tool, the experience described is confined to the NETSIM microscopic traffic simulation program (1). A brief description of the NETSIM program is presented in the following section.

NETSIM PROGRAM

The NETSIM program is a microscopic traffic simulation model developed for FHWA to evaluate traffic control strategies in urban street networks. NETSIM (formerly called UTCS-1) was designed for use by both researchers and practitioners. The basic NETSIM model enters individual vehicles into a network through source nodes and entry links. As each vehicle is generated, it is stochastically assigned a set of performance characteristics, such as vehicle type, average discharge headway, average acceptable gap, etc. Each vehicle's movement through the network is then controlled by its assigned performance characteristics and microscopic car-following, queue-discharge, and lane-switching algorithms and by the assigned link turn percentages. The basic model has the capacity to handle 99 intersections, 160 links, and 1600 vehicles at any one time. However, these limits may be increased by changing the dimensions of the arrays that define the size of these parameters.

NETSIM has the ability to simulate the effects of traffic controls ranging from a simple "STOP" or "YIELD" sign to a dynamic, real-time traffic control system. Signal controllers may be either actuated or pretimed, and bus operations can be analyzed. A major strength of the program is its ability to consider control strategies that other programs cannot. Program output includes a variety of measures of effectiveness normally of interest to traffic engineers (speed, delay, etc.) plus estimates of fuel consumption and emissions for each vehicle type. A complete description of NETSIM's capabilities, inputs, and outputs is contained elsewhere (1).

As in any model that attempts to duplicate real-world conditions, NETSIM has its limitations. The program has been found to operate more effectively under heavy traffic conditions than in light, undisciplined flow (1). However, the model has been validated for isolated intersections (2), even though it was developed primarily for network applications.

PERSPECTIVE

The NETSIM program has been used by us and others for a variety of research purposes. Some perspectives on the type of research for which we have used the program and to some extent the frequency of its use follow.

NETSIM has been used at VPI by undergraduate and graduate students and faculty. Student use takes place in the form of independent studies, sponsored research, or thesis research, rather than as part of any regularly scheduled course. A large part of our NETSIM-related research has been concerned with determining the signal-setting requirements that minimize fuel consumption for isolated intersections and for open and closed networks, as opposed to evaluation of types of control strategies. On occasion, observations during these studies have led us to examine some aspects of the program itself, although such examinations have been performed only to ascertain accuracy of program output. In summary, then, we are occasional users of the program and should by no means be considered NETSIM "experts".

Research Applications

Most of the NETSIM-related research at VPI has dealt with the effects of signal settings on fuel consumption. The need for studies of this type first became apparent with the oil embargo of 1973, when the nation was suddenly made aware of its dependence on foreign oil. Traffic researchers began asking questions such as the following:

1. Can traffic signals be timed to minimize fuel consumption (rather than delay)?
2. If so, what are the potential fuel savings?
3. If, indeed, signals can be timed to minimize fuel consumption, what delay penalties are involved?

Most early studies addressed the problem of pretimed controls at isolated intersections. Unfortunately, the results of these studies were not consistent. Some investigators (3,4) concluded that extremely long cycle lengths were required to minimize energy consumption, while others (2,5) found that the same cycle length that produced minimum delay also minimized energy consumption. Although researchers are still not in agreement on the answer to this question, it is important that it be resolved because the impacts on both fuel consumption and motorist delay can be significant. It should be noted here that the Cohen and Euler study (2) was based on the NETSIM program.

Traffic-Actuated Control

Perhaps the first investigation of energy consumption characteristics related to traffic-actuated contol was that completed at VPI in 1979 (6). This study was concerned with net energy consumption, not only fuel consumption. Net energy analysis considers all energy used in all primary forms in vehicle operation. For example, a vehicle stop causes extra tire wear (in addition to extra fuel consumption and other items), and this extra wear has an energy cost associated with it. The study, then, was concerned with the actuated signal settings that minimized net energy consumption. The associated impact on delay was evaluated. Although NETSIM does not calculate net energy consumption, it was possible to develop a simple model that estimates net energy consumption based on NETSIM output. Since macroscopic techniques for analyzing actuated control did not exist and the necessary resources for conducting field studies were not available, NETSIM was the logical tool to use for the study. The NETSIM output data needed to determine net energy consumption were vehicle miles of travel, vehicle trips, average delay per vehicle, percentage stopped delay, and stops per vehicle.

The findings of this study will not be stated here because the results must now be considered suspect. The reasons for this are twofold. First, we discovered several months after publication of the study results that the NETSIM model generates vehicles based on a uniform statistical distribution and not according to the shifted negative exponential distribution as was done in UTCS-1. We know of no place where this change is documented. This program change should have negligible impact on simulations of large networks under high volumes, since car-following laws would govern soon after the vehicles are generated. This is hardly true, however, for isolated intersections under low-to-moderate volume conditions. The second reason is an apparent inconsistency in stops per vehicle and number of cycle failures as given in NETSIM's output.

TRANSYT Studies

NETSIM was used as a baseline program in two studies. The first study dealt with evaluating the effect of different optimization schemes on signal settings as dictated by the TRANSYT-7 program for an open network (7), and the second study investigated the effect of signal settings optimized by the same TRANSYT version on traffic operations. TRANSYT is a macroscopic simulation program that, for a given cycle length and phasing pattern, uses a performance index (PI) to optimize offsets and cycle splits in a network. The PI in the TRANSYT-7 program is a weighted sum of stops and delays. Mathematically, the performance index may be written as follows:

$$PI = \sum_{i=1}^{n} (d_i + KC_i) \qquad (1)$$

where

n = number of links in the network,
d_i = average delay on link i (vehicle-hours/hour),
C_i = average number of stops per second on link i, and
K = user-specified weighting factor (stop penalty).

The objective of the first study was to evaluate the traffic operation in an open network in which signal settings were determined by minimizing (a) total vehicle delay, (b) total passenger delay, (c) excess fuel consumption due to idling and speed-change cycles, and (d) total cost. The selected network, comprised of a six-lane arterial street intersected at five locations by two- and four-lane streets, was part of the Washington, D.C., network used for validating the UTCS/BPS computer program (8). The arterial had light traffic flows with an average of 300 vehicles per hour per lane. On a per-lane basis, the cross-street traffic volume was heavier than that of the arterial at three of the five intersections. Bus volumes over portions of the arterial reached 85 buses/h. Cross-street bus volumes ranged from 5 to 54 buses/h.

The PI in TRANSYT was modified to simulate the four optimization strategies mentioned earlier, and NETSIM was modified to generate vehicles based on a shifted negative exponential distribution. A range of cycle length of 40-90 s was adopted for the network. TRANSYT optimum cycle length and NETSIM optimum cycle length were then observed for each optimization strategy. It was concluded that

1. There is agreement between both programs on the optimum cycle length for minimizing the total vehicle delay and the total network cost.
2. There is a slight difference between the two programs on the optimum cycle length for minimizing the total passenger delay.
3. There is a large discrepancy between NETSIM and TRANSYT cycle lengths with regard to the fuel consumption logic.

A primary objective of the second study was to find the stop penalty (or a function describing it) that would provide the signal settings for minimizing fuel consumption in a network. Two networks were analyzed. One, a four-intersection open network in Blacksburg, Virginia, carried low-to-moderate traffic volumes. The second network, located in Arlington, Virginia, contained 24 intersections (20 of which were signalized) and carried high volumes of traffic. Since the TRANSYT-7 program version did not provide fuel consumption estimates, it was necessary to use NETSIM to obtain them. (It should be noted that more recent versions of TRANSYT not only include estimates of fuel consumption and emissions but also use a greatly expanded performance index function so that one can, if desired, perform optimizations based on fuel consumption alone.) For purposes of this study, NETSIM was modified to generate vehicles based on a shifted negative exponential distribution, as was done in UTCS-1. Results of the study showed strong relationships between fuel consumption and both average total delay per vehicle and average stopped time per vehicle. It was also shown that for these two networks the settings that produced minimum delay minimized fuel consumption. A TRANSYT stop penalty of zero should have produced this effect, but did not (based on NETSIM output). In fact, there appeared to be no consistent relationship between stop penalty and fuel consumption. These and other results of the study are contained in a thesis by Hill (9).

Sensitivity Study

The fuel consumption tables embedded in NETSIM are based on an analytical model developed by the Transportation Systems Center (10). It appears, however, that most researchers attempting to model fuel consumption requirements at intersections use Claffey's data (11). Claffey's data are the result of field testing of fuel consumption of highway vehicles under various operating conditions. However, the form in which Claffey's data are given is not compatible with that required by NETSIM, although NETSIM does have the flexibility of accepting alternative fuel consumption tables if the user wishes to provide them. Conversion of NETSIM's fuel consumption data to the form in which Claffey's data are presented revealed that, although the two data sets exhibited similar trendwise behavior, fuel consumption magnitudes were often quite different. A procedure was developed that converted Claffey's data to the NETSIM format and calibrated them for NETSIM's vehicle trajectory profile (12).

The primary purpose of the study by Hurley and others (12) was to ascertain whether or not significant differences existed in NETSIM output between the two fuel consumption models and also between the uniform distribution model used to generate vehicles and a shifted negative exponential distribution. Also studied was the sensitivity of fuel consumption and delay to saturation headway (or saturation flow rate). The effect of grade on fuel consumption and delay was investigated, although only in part because the NETSIM fuel consumption logic does not consider grade effects. That is, the effect of grade on saturation headway was considered, but the direct effect of grade on fuel consumption was not.

Most of the study conclusions were based on data generated for an isolated intersection under pretimed control, although comparisons were made for the same open network in Blacksburg referred to earlier. Conclusions reached from the study were

1. NETSIM's embedded fuel consumption data produced significantly lower consumption estimates than did the Claffey-based tables.
2. Significant differences were found in fuel consumption and delay output between the uniform and shifted negative exponential models for generating vehicles.
3. NETSIM fuel consumption and delay outputs are sensitive to saturation headways greater than 2.2 s.
4. Within the limits of the investigation, grade effects appear to significantly affect fuel consumption and delay only at high volumes.

RECOMMENDATIONS FOR IMPROVEMENTS

The NETSIM-related research described in the preceding section provides only a partial picture of our experience with the program. The following points out known and suspected problems in the program itself, some problems with and suggested improvements for the program documentation, and simple changes in program output that (from our viewpoint) would be helpful to the user.

Internal Logic

Cycle Failures

In the study of actuated controllers, it was observed that the program consistently contained zeros in the cycle failure column, regardless of input volume magnitude. This should be corrected.

Stops per Vehicle

Examination of NETSIM output for Blacksburg's open network showed that for one intersection the number of stops per vehicle was greater than 1. At the same time, there were only 5 cycle failures out of 48 cycles. We know of no logical explanation for this inconsistency, and it seems to us that the logic is incorrect for either stops per vehicle or for cycle failures (under pretimed control). We suspect that the stops-per-vehicle logic is at fault, since the signal timing was such that there should be few, if any, cycle failures for the approach volumes.

Dual-Ring Controllers

In a non-research application of NETSIM, operation of a four-intersection coordinated network in York County, Virginia, was to be evaluated. One of the controllers in the system was a dual-ring actuated controller. The average delay value for the intersection was estimated to be an obviously incorrect 372 s/vehicle by NETSIM. A similar estimate for the intersection assuming pretimed control was "only" 109 s/vehicle. The dual-ring logic is obviously faulty.

Grade Effects

Although the published results of our study addressed the effect of grade on fuel consumption related to passenger cars only, a cursory examination was made on the effect of grade when the traffic stream consisted of 15 percent trucks. No differences in either delay or fuel consumption were observed for grades between -5 and +5 percent that could not be attributed to randomness. If the differences are not due to randomness, then they are trendwise illogical. We suspect, then, that grade is not taken into account at all in the simulation, although grade is a program input item. This should be investigated and, if need be, corrected.

Headway Distribution

The findings of the sensitivity analysis show that delay and fuel consumption output is significantly different when the shifted negative exponential distribution is used to generate vehicles rather than the uniform distribution. It is not known for certain why the vehicle-generation logic was changed when UTCS-1 evolved into NETSIM, and no claim is made here that the shifted negative exponential distribution is the best one to use. However, in the interest of providing more valid output for small networks and isolated intersections under low-to-moderate volume conditions, the uniform headway distribution logic shouuld be replaced or made a user option.

Fuel Model

The sensitivity analysis showed a significant difference in fuel consumption output between the Claffey-based fuel model and that embedded in NETSIM. Again, no claim is made as to which is best. Both data sets are old and not representative of current vehicle population. Since it has been shown that these differences can be significant, we feel that a newer data base should be obtained and that such data should be based on field tests of fuel consumption. It is also recommended that the fuel model be expanded to consider the direct effects of grade on fuel consumption. This would not be a simple modification. Neither would it be an impossible one.

Program Output

The following are program output changes that we feel would be useful. Some would logically be program options.

1. Average queue per lane is a possible addition.
2. Intermediate network statistics as an option do not work as stated in the user's manual. When they do work, fuel consumption data are not included. One can, however, get cumulative intermediate results.
3. Average saturation percentage, information that is perhaps useful to some users, is improperly titled. To us, average saturation percentage is synonymous with degree of saturation; that is, demand flow rate divided by the product of saturation flow rate and the portion of the cycle that is effectively green. The average saturation percentage as output by NETSIM is the timewise average of link occupancy divided by total link storage capacity. It is felt that most users are familiar with the signal-related definition. In addition, output of degree of saturation (according to the signal-related definition) would be extremely valuable.
4. Fuel consumption output data in gallons per vehicle would be helpful because consumption expressed in total gallons can be misleading.
5. Lane occupancy output would be another very useful addition to program output.
6. Subinterval statistics as an option would include measures of deviation within each subinterval. Some possibilities are maximum delay, minimum delay, standard deviation of delay, ratio of standard deviation to the mean, and 85th percentile speed and 10-mph pace. It is not known if the program can provide the reliable data at this level of detail.

Program Documentation

The primary change that we feel should be made in the program documentation is in the form of an addition to the user's manual. The suggested addition would be a guide to the user that describes pitfalls commonly encountered by the new or occasional user and, most importantly, the limitations of the program concerning what it should or should not be used for. For example, we are not certain that the type of research described in this paper does not exceed the accuracy limitations of the NETSIM model. Certainly, one is on potentially shaky ground when he or she attempts to evaluate one simulation program on the basis of another's output, as was done with TRANSYT-7. If this is the case, it should be emphasized in the user's manual. Furthermore, if NETSIM as it now exists is not accurate enough to support research such as this, every effort should be made to make it so. The time and dollar costs required to collect and analyze field data for the research described in this paper would be prohibitive.

With regard to new user pitfalls, the suggested addition should contain guides about the number of runs or replications required to produce acceptable accuracy and warnings about the sensitivity of program output to random number seeds. For example, an analysis for an isolated intersection was made by using a total of nine replications. It was found that by increasing the number of replications from three to six, the ratio of standard deviation to the mean (for delay) increased. By using nine replications, the ratio decreased. A user could draw two possible conclusions from this: (a) three replications are sufficient or (b) more than nine replications are needed. Our studies also showed that there was more variation in data when vehicles were generated according to the shifted negative exponential distribution.

A final suggestion is that FHWA use some type of designation to distinguish different versions of NETSIM. Improvements are continually being made to the program, but it is difficult for the occasional user to know if the program version being used is the latest one. Perhaps numerical or alphabetical designations such as are used for other programs (e.g., TRANSYT-7, TRANSYT-6C, etc.) would be sufficient. Obviously, program documentation should be revised to reflect any program changes made. The existence of new modifications should be publicized to alert the user to them.

CONCLUSIONS

This paper has summarized the experiences, problems, and recommendations of researchers at one university relative to the use of the NETSIM program as a research tool. In our opinion, NETSIM is a useful and comprehensive program that could and should be made better. It is possible that the developers of the program never intended it to be used for the type of research illustrated here. Nevertheless, NETSIM's comprehensiveness and relatively low costs (when compared with the alternative of collecting and analyzing sufficient field data) will continue to make it attractive to researchers. It is felt, therefore, that efforts required to improve program accuracy would be highly beneficial to both researchers and practitioners.

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Simulation Developments in Progress

Guido Radelat

Traffic simulation is, at the present time, a very dynamic discipline. It is growing fast because it is still a young discipline where dogmas are few and new ideas are welcome. It is changing rapidly because it is closely linked with the rapid and continuous advances of the digital computer. Because it is almost impossible to follow all the developments that are taking place in traffic simulation, this discussion will be concerned only with the traffic simulation activities performed and sponsored by FHWA.

TYPES OF TRAFFIC SIMULATION ACTIVITIES

In the traffic simulation discipline there are two major skills involved: modeling and computer programming. These skills are so interrelated that sometimes it is difficult to distinguish one from the other; nonetheless, they are different.

Modeling is the representation of a real-life system by a more manageable system. Programming is the translation of modeling logic into a language that the electronic computer can understand. In general, modeling precedes programming, but the transition between these tasks is usually blurred. Very often there is considerable overlapping and the last details of a model are completed as a program is developed. This is one of the reasons why simulation models are frequently called simulation programs.

Six types of traffic simulation activities can be defined:

1. New model development,
2. Testing,
3. Implementation,
4. Enhancement,
5. Application, and
6. Maintenance and support.

The following paragraphs describe these activities.

New Model Development

Twenty years ago, when many doubts existed about the feasibility of simulating traffic on a computer, the development of a new model was considered the only worthwhile activity in this field. Now, model development is only a small portion of the efforts usually involved in traffic simulation. New model development consists of

1. Requirement analysis, which is the identification of the needs for the model and the functions it should perform;