vehicle (using a specific point of reference such as the front wheel) between two unobtrusive transverse pavement markings extended across all lanes and spaced 91 m (300 ft) apart. Dark green paint or tape may be used for markings. It is clearly visible to an observer, yet would probably not be detectable to the driver. One very important aspect of this procedure is to obtain a random sample of the total vehicle population. Common observer bias, for instance, too-frequent sampling of large or fast vehicles, in collecting spot data must be avoided. Approximately 60 vehicles can be sampled in a period of 30 min. Using this sample, the mean and standard deviations will be calculated as a baseline against which speeds of slow vehicles are compared.

Slowly traveling vehicles can be timed during alternate 30-min periods. Our manual coding reliability study demonstrated that vehicles traveling one standard deviation below the mean speed can be correctly estimated in 80 percent of the cases. The field procedure suggested here is to time all vehicles appearing to meet the slow-driving criterion; data on those actually traveling faster than one standard deviation below the mean speed can be discarded during the subsequent data reduction.

The measure obtained will be the proportion of exiting traffic volume meeting the slow-speed criterion. Each lane must be separately analyzed for speed variations between lanes. Since trucks, particularly large combinations, are generally driven by professional drivers, a general procedural suggestion for data collection is to observe automobiles and trucks as separate subpopulations.

ANALYSIS OF DATA

Recorded data must permit analyses of vehicle behavior as a proportion of exit volume. Comparisons of before data between test and control sites in an experiment provide a check of site configuration match. Before-and-after differences at the test site provide a gross indication of the impact of guide signing changes. Comparative before-and-after differences and the test versus the control site provide a rigorous indication of signing change impact with the time element effectively factored out and the effects of confounding variables minimized.

For each of these comparisons, it is important to use data that are collected during corresponding time periods. It is suggested that traffic volume differences be first examined for significant differences between the before-and-after condition using the chi-square test. Proper designation of before-and-after data collection periods (1-year interval) will likely result in insignificant volume differences. In this case, one should examine differences in target behavior occurrence, using the chi-square test to make the comparisons cited above. If before-and-after volumes differ, one should convert traffic behavior data to proportions of exiting traffic volume and perform the comparisons using the z-test to determine significant differences. The conversion to proportions should reduce the likelihood of spurious results caused by changes in volume.

A reduction in the frequency of the behavior types designated in Figure 1 should indicate that a measurable benefit was elicited by the signing change. The significance tests described above are the primary means for determining changes in MOE behavior.

ACKNOWLEDGMENT

The work reported in this paper was sponsored by the American Association of State Highway and Transportation Officials, in cooperation with the Federal Highway Administration, and was conducted in the National Cooperative Highway Research Program. Opinions and conclusions expressed in this paper are solely those of the authors.

REFERENCE

1. F. R. Hanscom and W. G. Berger. Motorist Response to Highway Guide Signing. Report prepared by BioTechnology, Inc., Falls Church, VA, Jan. 31, 1976, for NCHRP, Project 3-21.

Publication of this paper sponsored by Committee on Methodology for Evaluating Highway Improvements.

Abridgment

Macroscopic Simulation Models for Use in Traffic Systems Management

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In recent years, traffic simulation has become a powerful tool for testing alternate traffic control strategies. The NETSIM (formally UTCS-1) network simulation model (1) was developed for the Federal Highway Administration for this purpose and has found increasingly widespread application.

More recently, the favored approach to urban transportation problems has shifted from traffic control to transportation systems management (TSM). Here, too, simulation should be a powerful tool in testing alternate strategies. These strategies, however, will in general be very different from the pure control strategies developed previously in that they will involve route changes.

Unfortunately, the NETSIM model, which is so successful in testing these strategies, is inappropriate for testing many TSM strategies because of its microscopic vehicle-tracing interactions. This microscopic approach is responsible for the flexibility and accuracy of UTCS-1 but is too expensive in terms of computer time and core to be used on networks larger than 40-50 intersections. Thus, it is evident that a model that does not track individual vehicles is needed to test TSM strategies.

MACROSCOPIC NETWORK MODELS

Three existing macroscopic models, TRANS (2), TRANSYT (3), and SIGOP-II (4), were chosen for comparison. They were executed on a network in Washington, D.C., for which both input and measures of effectiveness (MOE) data were available. The MOE average speed computed by these models was then compared with field data and a NETSIM run of the same network.

TRANS Model

The TRANS model divides each link into zones of length T/S, where T is the time scan length and S is the free-flow speed. Vehicles are moved from the zone currently occupied to the next downstream zone, which is either on the same link (intralink movement) or the next downstream link (interlink movement). Traffic movements may be impeded, and vehicles enter into the queue state when (a) the zone immediately downstream is full, (b) the vehicle is in the downstream zone and faces a red signal indication, (c) the vehicle is a left turner in the downstream zone facing an unacceptable gap in oncoming traffic, and (d) the vehicle is a right turner in the downstream zone facing pedestrian interference.

In the queue state, vehicles discharge in a hit-or-miss Monte Carlo approach based on the mean queue discharge headway input for each link.

Left turns and right turns on red (RTOR) are simulated by using gap-acceptance logic. When a vehicle is discharged from the last zone on a link, the rest of the vehicles in queue are moved up in the next time step to fill the vacancy. Thus, the queue-discharge expansion wave is not modeled, and cases where spillback conditions may be expected to prevail are not properly modeled.

The version of the model used here, TRANS-IV, allows pretimed signals and midblock sinks and sources, but there is no platoon dispersion feature or any internal provision for trucks and buses or midblock rare events.

TRANSYT Model

The TRANSYT model is used as an off-line program to optimize signal settings. The evaluation portion is a simulation model that is more macroscopic than TRANS in that the detailed intersection performance is not modeled. Delay is calculated using an algorithm based on these parameters: volume-to-capacity ratio (V/C), green time, and offset, together with a platoon dispersion algorithm. For links with V/C > 1, queue buildup is computed.

The platoon dispersion algorithm, which is applied to both the primary and secondary flows on a link, is a recurrence relation based on exponential smoothing that has been validated in the field by the Transportation and Road Research Laboratory in Great Britain.

Two types of delay, uniform and random, are calculated. Uniform delay is based on the assumption that the traffic pattern is static from cycle to cycle, while random delay is based on fluctuations from uniformity and is determined by the V/C ratio. This latter term can contribute quite substantially to the total delay for intersections near saturation.

The version of the model, TRANSYT V, used in this exercise simulates pretimed signals and midblock sources but does not treat buses, trucks, turning movements, midblock rare events, midblock sinks, or RTOR.

SIGOP-II Model

The SIGOP-II model, like TRANSYT, is used as an off-line program to optimize signal settings. The evaluation portion is a simulation model similar to that of TRANSYT but with some major differences: (a) SIGOP-II assumes that all platoons are rectangular in shape; (b) a random component of delay is not calculated; (c) continuity of platoon structure beyond the intersections immediately surrounding each intersection is not maintained as rigorously as in TRANSYT; and (d) the case where V > C is not treated. If a flow occurs with V > C, it is truncated. On the other hand, a correction is made to the free-flow speed to account for acceleration and deceleration effects at the link ends. This correction has a substantial effect on simulated average speeds.

The SIGOP-II model internally handles turning movements, trucks, and buses by converting them to equivalent passenger-car units (PCUs). Thus a truck is considered 2.25 PCUs and a right turn as 1.25 PCUs; a left-turn equivalent is determined by using an algorithm developed by Fellinghauser (5). Sinks and sources and pretimed signals are simulated, but not RTOR.

The table below gives a comparative summary of the models.

	Model		
Element	TRANS	TRANSYT	SIGOP-II
Platoon dispersion	No	Yes	Yes
Turning impedance	Gap acceptance	None	Equivalent PCUs
Data updating	Yes	No	No
Queue discharge	Monte Carlo	None	None
Trucks and buses	No	No	Equivalent PCUs
Midblock events	No	No	No
Pedestrian blockage	Delay right-turn discharge	No	Equivalent PCUs
Computer language	IBM 7090 Assembly	FORTRAN IV	FORTRAN IV
RTOR	Yes	No	No
Free-flow speed correction	No	No	Yes

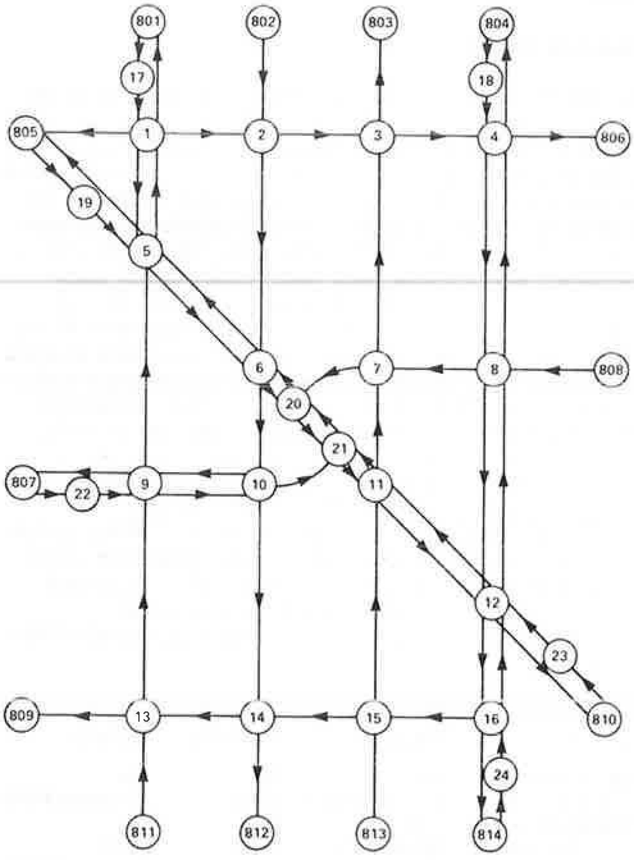
SIMULATION TEST CASE

In order to test the models for accuracy and computer time requirements, they were executed using a data set (1) gathered for the purpose of validating the UTCS-1 model. The data set used consisted of 32 min of morning peak data collected by aerial photography on a 16-intersection network (Figure 1) in downtown Washington, D.C.

This data set was chosen because it includes accurate MOE data that allow a good comparison of model accuracy. Complete information was available on volumes, turning movements, vehicle types, lane blockages, bus movements, signal settings, pedestrian volumes, and midblock sink and source volumes. When the data were reduced during the UTCS-1 validation (1), the 32-min period was split into eight 4-min intervals over which the data were aggregated. However, TRANSYT and SIGOP-II are static models and do not include a data update feature. For this reason, the eight 4-min subintervals were aggregated into one 32-min interval.

The following features that are available in some models but not in others were represented in the latter in order to make the accuracy comparison of the models as independent of these features as possible.

Figure 1. Network in downtown Washington, D.C.



1. Turning movements. SIGOP-II algorithms were used externally in TRANSYT to convert the input volumes to equivalent PCUs.
2. Source and sink volumes. TRANSYT provides for sources only. Sinks were added by inserting an extra link at each node that was the tail of a link with a sink. Sink traffic was diverted onto this exit link.
3. Stop signs. In Figure 1, nodes 9, 10, 20, and 21 are stop signs that only UTCS-1 simulates. These nodes were handled in the other three models by replacing them with sinks and sources.
4. Buses and trucks. The same factor of 2.25 PCUs used in SIGOP-II was externally introduced into the volume inputs for TRANS and TRANSYT.
5. Exclusive turning lanes. These were introduced in TRANSYT by assignment of separate links.
6. Midblock lane blockages. These are treated by UTCS-1 but not by the other three models. No easily implementable way was found to represent this effect in the other three models.
7. Free flow speed. The same link-specific free-flow speeds were chosen for all models. This was because the average running speeds that should be used in TRANS and TRANSYT were not available (the other two models take account of the link end acceleration and deceleration effects).

TEST CASE RESULTS

Using the data set described above, the four models were executed. Three replication runs were made using UTCS-1. UTCS-1, TRANSYT, and SIGOP-II were executed on the U.S. Department of Transportation's IBM-360-65, while the TRANS model was executed on an IBM-7090. Comparative computer times for the 32-min period were about 13 min for UTCS-1, about 6 min for TRANS, about 6 s for TRANSYT, and about 22 s for SIGOP-II.

The four MOEs that most stringently test model operation are travel time, average speed, stops, and total delay. The number of stops was not available in the field data. Travel time is not meaningful unless related to some distance traveled, and total delay is dependent on a free-flow speed. Average speed, on the other hand, relates travel time to distance traveled and is more independent of free-flow speed than total delay. Thus, average speed was chosen as the MOE to be used to compare the models.

The link-specific and overall results for average speed are given in Table 1. Only those network links that appear in all models are tabulated and included in the networkwide results, which indicate that, as expected, UTCS-1 performed the best, followed in order by TRANS, SIGOP-II, and TRANSYT. To determine the link-specific comparative performances, the sum of squares of the differences between each model's predicted link-specific average speed and the field value was calculated. Each term was weighted by the link volume. The results were UTCS-1: 413 027 $(km/h)^2$ (159 471 mph^2); TRANS: 1 397 663 $(km/h)^2$ (539 641 mph^2); TRANSYT: 1 449 471 $(km/h)^2$ (559 644 mph^2); SIGOP-II: 1 022 589 $(km/h)^2$ (394 824 mph^2).

DISCUSSION OF RESULTS

Several conclusions can be drawn or inferred from these results.

The SIGOP-II model performed better than TRANSYT in that the results were in closer agreement with the field data. However, this result is possibly misleading because it is probably the result of the free-flow speed correction in SIGOP-II. This correction is especially important in a network with short block spacing such as

Table 1. Comparison of simulated and field results for average speeds.

Link	Simulation Results (km/h)				Field Results (km/h)
	UTCS-1	TRANS	TRANSYT	SIGOP-II	
(5, 1)	21.50	21.1	21.50	20.6	21.13
(1, 2)	17.36	28.5	21.37	18.8	19.47
(2, 3)	16.48	19.0	18.26	21.6	20.45
(7, 3)	17.15	26.9	26.87	23.0	14.66
(3, 4)	12.45	14.0	14.25	17.0	14.85
(8, 4)	7.72	14.3	16.36	9.8	8.93
(1, 5)	20.23	9.9	20.37	28.0	7.87
(13, 5)	13.50	26.6	17.44	16.7	24.93
(6, 5)	12.47	19.1	14.27	8.0	13.14
(2, 6)	11.24	11.9	12.28	10.2	12.71
(5, 6)	20.58	23.6	21.48	20.1	17.29
(11, 6)	11.02	4.5	9.33	15.3	16.10
(11, 7)	21.59	25.3	23.80	16.7	18.66
(8, 7)	15.80	32.2	20.78	23.6	16.17
(4, 8)	13.77	11.9	18.37	17.5	9.67
(12, 8)	27.11	27.0	33.50	36.5	17.63
(6, 11)	22.53	29.3	39.92	27.8	20.77
(15, 11)	14.34	17.0	16.86	13.4	13.90
(12, 11)	23.78	25.4	26.97	20.8	22.14
(8, 12)	14.79	23.8	16.48	13.4	11.91
(11, 12)	24.73	13.4	28.19	25.9	18.52
(16,12)	6.45	7.7	6.40	6.00	6.85
(14, 13)	10.64	10.9	11.33	9.20	17.23
(6, 14)	28.22	38.0	35.93	31.85	25.60
(15, 14)	14.01	11.6	13.72	16.90	10.36
(16, 15)	18.48	19.1	18.58	34.3	13.26
(12, 16)	28.18	36.7	29.81	24.0	27.80
Network-wide	15.70	17.28	19.52	17.76	15.85

Note: 1 km/h = 0.62 mph.

was chosen for this study. Further, only one link has a V/C ratio value approaching 1, which yielded a substantial random delay contribution. Thus, it is possible that SIGOP-II might not perform better than TRANSYT in a network with more links having V/C ratios near 1 and longer block lengths (or, in fact, if a similar free-flow speed correction factor were applied to TRANSYT).

The results of TRANS and TRANSYT were mixed. TRANS was closer to the field data on a networkwide basis, but in the link-specific sum of squares test, the two models were about even. The reason can be seen from looking at the link-specific results; TRANSYT almost consistently gives a higher value for average speed than is observed in the field, while TRANS often gives a lower value. It is highly probable that the reason why TRANSYT is consistently high is the use of free-flow speed rather than average running speed, which will also be a factor in the TRANS model. In the latter, however, the hit-or-miss Monte Carlo queue-discharge mechanism is equivalent to a negative exponential headway distribution (6). This means that there will be some probability of long headways being generated. These are not observed in field data, unlike UTCS-1 in which the longest headway is 1.8 times the mean headway. This will have the effect of overestimating delay on an intersection approach in which V/C approaches 1.

REFERENCES

1. R. D. Worrall and E. B. Lieberman. Network Flow Simulation for Urban Traffic Control Systems—Phase II. Federal Highway Administration; National Technical Information Service, Springfield, VA, 1973, Vols. 1-5.
2. F. A. Wagner, F. C. Barnes and D. L. Gerlough. Refinement and Testing of Urban Arterial and Network Simulation. U.S. Department of Transportation; National Technical Information Service, Springfield, VA, 1967.
3. D. Robertson. TRANSYT—Users Manual. Federal Highway Administration; National Technical Information Service, Springfield, VA, 1974.
4. E. B. Lieberman and J. L. Woo. SIGOP-II: Program to Calculate Optimal, Cycle-Based Traffic Signal Timing Patterns. Federal Highway Administration; National Technical Information Service, Springfield, VA, 1976.
5. E. Fellinghauser and D. S. Berry. The Effects of Opposing Flow on Left-Turn Reduction Factors at Two-Phase Signalized Intersections. Paper presented at the 53rd Annual Meeting, TRB, 1974.
6. S. M. Ross. Applied Probability Models With Optimization Applications. Holden-Day, San Francisco, CA, 1970.

Publication of this paper sponsored by Committee on Traffic Flow Theory and Characteristics.

Some Properties of Freeway Density as a Continuous-Time, Stochastic Process

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Density is an important macroscopic parameter of traffic flow. A number of studies have based estimations of the density on a section of roadway on speed and flow measurements at the section entrance and exit. This paper views density as a continuous-time, stochastic process and considers the characteristics of the process itself. The study relied on freeway traffic data previously obtained by sequential aerial photography. Position data were smoothed and interpolated to construct individual trajectories, which were aggregated to obtain continuous vehicle counts in roadway sections of various lengths. Autocorrelation functions and power spectra were calculated for these records. It was found that, for the traffic flow under consideration, correlation time was proportional to freeway section length. The power in the process was concentrated below a cutoff frequency that was inversely related to section length. The implications these results have for sampling real traffic processes are discussed.

Density was recognized as an important parameter early in the study of traffic flow. For example, Greenshields (1) concluded that time mean speed was a linear function of density in vehicles per kilometer. His density, the ratio of flow to the arithmetic average of the speeds of vehicles passing the measurement point, is now known to be a biased estimate of the number of cars on a given roadway section (2, 3).

A number of studies have considered the problem of basing estimations of density on a section of roadway on speed and flow measurements at the section entrance and exit (4, 5, 6, 7, 8, 9). This study views density as a continuous-time, stochastic process and considers some of the characteristics of that process.

The data for this study were originally obtained by taking sequential aerial photographs of a three-lane section of the westbound Long Island Expressway (10). The selected flow sequence had a mean concentration of 9.3 vehicles/lane-km (15 vehicles/lane-mile). This corresponds to the Highway Capacity Manual (11) level of service B. The four test sections, 91, 305, 558, and 853 m (300, 1000, 1830, and 2800 ft) long, are examined in column 1 of the table below (1 m = 3.3 ft).