Evaluation of Network Traffic Performance Measures by Use of Computer Simulation Models

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The relation between traffic-signal-timing parameters and selected traffic performance measures of effectiveness (MOEs) was investigated by computer simulation of peak-hour flow conditions on an urban arterial in Madison, Wisconsin. The MOEs included delay, stops, fuel consumption, and exhaust emissions. A variety of signal-timing plans were generated by using time-space diagram methods and the TRANSYT signal-timing optimization model. Two computer simulation models, TRANSYT and NETSIM, were then used to develop traffic performance data for evaluation purposes. The results of the study showed that the signal-timing parameters that had the most significant effect on the MOEs were cycle length and the K-factor in the TRANSYT performance index. Speed of progression was highly correlated with number of stops: A higher value yielded a lower number of stops. Priority policy and split method did not show a significant impact on the MOEs. All MOEs can be improved when optimized timing plans are used instead of those developed by time-space diagram methods. In a comparison of the TRANSYT and NETSIM simulation models, the NETSIM model produced higher values for the MOEs under a given signal-timing plan. In a comparison of MOEs, number of stops and NO_x showed a close correlation whereas delay appeared to be a strong surrogate for the other principal MOEs.

Traffic behavior variables such as delay and stops have traditionally been used as indicators of the level of performance of a variety of traffic operations and control strategies. However, since the oil embargo of 1973, automobile fuel consumption has received increasing attention as an additional important performance measure. Recent research dealing with fuel consumption as a measure of effectiveness (MOE) has produced inconsistent findings with respect to its relation to certain traffic signal timing parameters, as well as other MOEs.

For example, in 1975 Bauer (1) developed a model of fuel consumption at signalized intersections based on Webster's equation for intersection delay. Testing of the model revealed that the cycle length at which fuel consumption is minimized apparently is significantly greater than the cycle length at which delay is minimized (see Figure 1). In a subsequent investigation, Courage and Parapar (2) found similar results for a network of 26 signalized intersections in Gainesville, Florida. By using estimates of delay and number of stops from the TRANSYT computer model (3) and applying Claffey's (4) fuel-consumption coefficients for a composite vehicle on level ground with an approach speed of 30 miles/h, Courage and Parapar found that minimum delay would be achieved at a 90-s cycle length and fuel consumption would be minimized at a 140-s cycle length (see Figure 2).

Dissimilar findings were reported in a 1979 study by Cohen and Euler (5), who used the NETSIM traffic flow simulation model (6) to evaluate the relation among fuel consumption, vehicle emissions, delay, and signal cycle length for an isolated intersection with a two-phase, fixed-time signal. Cohen and Euler found that the cycle length at which minimum delay occurs is the same as that at which minimum fuel consumption occurs (see Figure 3).

Figure 1. Delay and energy consumption versus cycle length for intersection with total critical flow of 1400 vehicles/h.

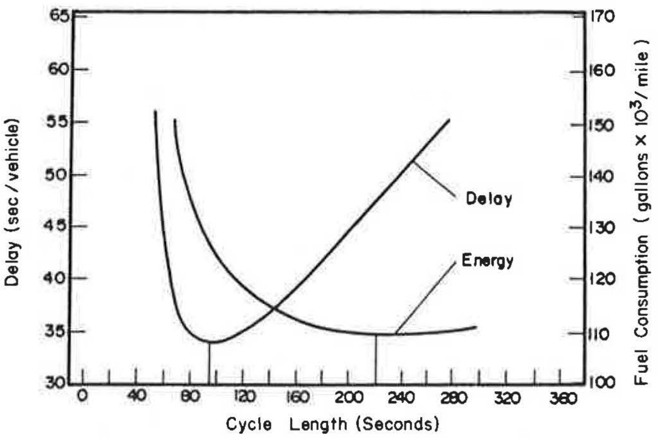


Figure 2. Fuel consumption and delay versus cycle length for signal system of Gainesville, Florida, central business district.

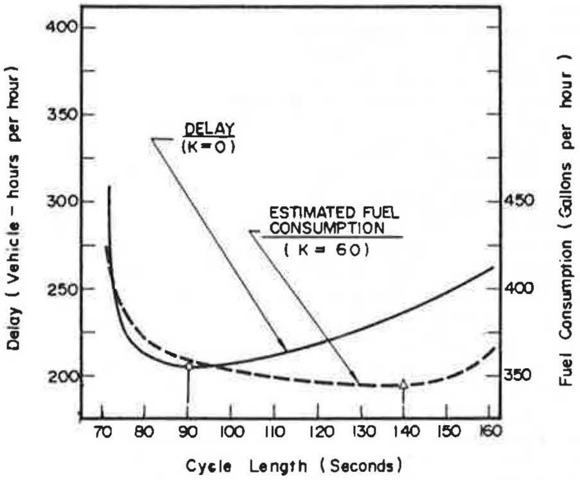


Figure 3. Fuel consumption and delay versus cycle length for isolated intersection with critical flows of 1800 vehicles/h (no left turn, 10 percent right turn) and 400 vehicles/h (no left turn, 20 percent right turn).

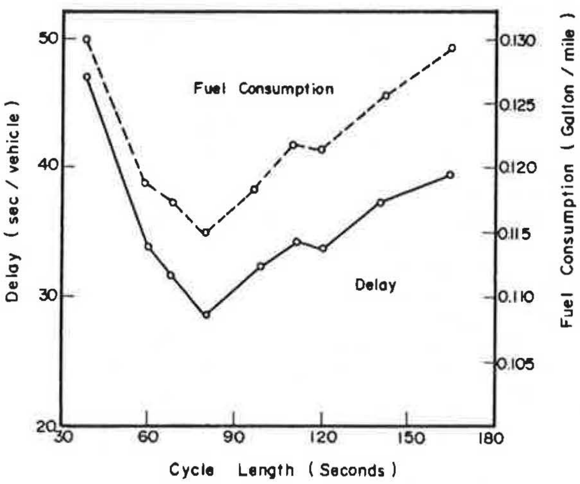
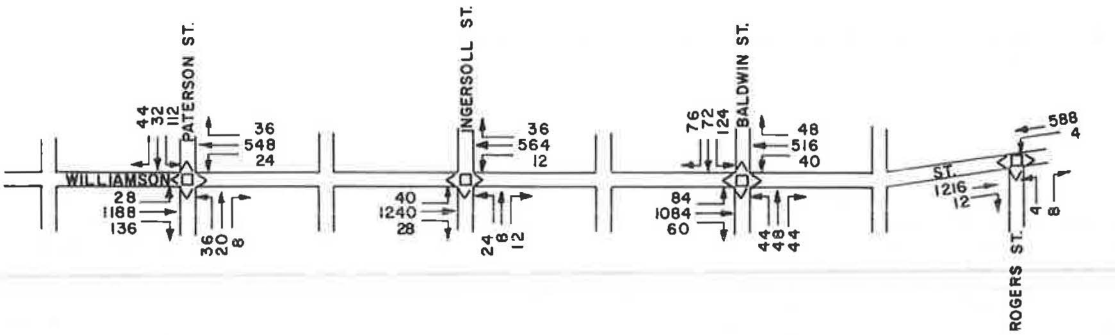


Figure 4. Peak-hour traffic flows for Williamson Street in Madison, Wisconsin.



The differences in the findings from these studies can probably be attributed to several factors. For example, both Bauer (1) and Courage and Parapar (2) applied Claffey's rate of idling fuel consumption (4) to the delay estimates produced by Webster's equation and the TRANSYT model, respectively. However, these delay values are estimates of overall delay, including that experienced during deceleration and acceleration. Therefore, the resulting estimates of fuel consumption attributable to the vehicle idling component would tend to exhibit an upward bias because of the inclusion of a certain amount of nonidling delay, especially when the proportion of stopped vehicles is high and average stopped delay is relatively small.

Another significant consideration is that the number of stops at an intersection is a more important factor in fuel consumption than is idling delay. For example, if one uses Claffey's composite fuel-consumption coefficients of 0.6 gal/vehicle-h of stopped delay and 0.01 gal/vehicle stop, a vehicle stop is equivalent to 1 min of idling delay in energy use, even though a vehicle stop without idling time causes less than 1 min of delay (for a 30-mile/h cruising speed, one stop-and-go cycle without idling delay causes about a 15-s delay).

In addition, the computer models that were used to estimate the number of stops do not yield directly comparable results. The TRANSYT model used in the Courage and Parapar study (2) can produce an overestimation of fuel consumption because any finite delay is assumed to cause a stop, even though in practice the vehicle involved may have undergone only a small deceleration and acceleration. On the other hand, the NETSIM simulation model accounts for the complete trajectory of each vehicle. However, because midblock delay and fuel consumption cannot be obtained separately from the NETSIM output, it is also difficult to isolate the intersection delay and fuel consumption that are affected by traffic-control signals. When the midblock delay on the links is small enough to be ignored, the NETSIM outputs of delay and fuel consumption can be considered to represent intersection traffic performance.

Another possible cause for the differing results of the previous studies lies in the queue-discharge logic of the models that were used. For example, the first vehicle in a queue accelerates directly up to cruising speed whereas cars farther back spend considerable time traveling at speeds lower than the cruising speed while moving up to the stop line. This type of movement generally consumes more fuel than traveling at the cruising speed. The microscopic queue-discharge behavior of the NETSIM model automatically includes this effect, whereas the TRANSYT model ignores it. The effect of multiple stops due to left-turning vehicles is also considered in NETSIM but not in TRANSYT. Consequently, in a strict sense, some of the output from these studies cannot be directly compared.

RESEARCH OBJECTIVES AND SCOPE

Given the above considerations, the primary objective of this research was to further evaluate the relations among delay, stops, fuel consumption, and vehicle emissions for various signal-control parameters at pretimed signalized intersections along an urban arterial under existing roadway and traffic-flow conditions (7). Although it would be preferable to examine a variety of urban arterial scenarios, cost and time constraints limited the research to a single case-study urban arterial.

The site selected for the study was a 5000-ft section of Williamson Street in Madison, Wisconsin (see Figure 4). Williamson Street is an arterial that has signalized intersections spaced 0.25 mile apart. Local street intersections occur between the signalized intersections, and traffic flow on the minor streets is relatively light compared with that on the arterial. Williamson Street is 50 ft in width and during peak hours operates with two traffic lanes in the peak flow direction and one traffic lane plus a parking lane in the opposite direction.

The experiments were designed to encompass a range of practical signal-timing plans developed by using both maximal-band-width time-space diagram methods and version 6C of the TRANSYT computer optimization program (8). Parameters such as directional priority, speed of progression, stop penalty, and split strategy were selectively varied. Both the TRANSYT and NETSIM computer models were used to simulate traffic performance under each of the timing plans. The resulting data were then subjected to statistical analysis by use of analysis of variance (ANOVA) techniques.

EXPERIMENTAL DESIGN

Research hypotheses were expressed in terms of the following seven questions:

1. Do the manually designed signal-timing plans and TRANSYT-optimized timing plans yield significantly different levels of performance?
2. Do the TRANSYT and NETSIM evaluation models yield significantly different results?
3. What is the effect of cycle length on each MOE?
4. Does the priority policy (peak-direction progression or balanced progression) make a significant difference?
5. What is the effect on MOEs of speed of progression in developing the manual timing plans?

Figure 5. Experimental design for manually developed timing plans.

Cycle Length (s)	Split	Priority Policy and Speed of Progression (miles/h)					
		Peak Direction Progression			Balanced Progression		
		20	25	30	20	25	30
60	Balanced V/C						
	Excess to arterial						
80	Balanced V/C						
	Excess to arterial						
100	Balanced V/C						
	Excess to arterial						
120	Balanced V/C						
	Excess to arterial						
140	Balanced V/C						
	Excess to arterial						

Figure 6. Experimental design for TRANSYT-optimized timing plans.

Cycle Length (s)	Priority Policy and K-Factor					
	Peak Direction Progression			Balanced Progression		
	K = 5	K = 60	K = 90	K = 5	K = 60	K = 90
60						
80						
100						
120						
140						

6. What is the effect of the TRANSYT stop weighting factor on MOEs?
7. Does the split strategy [balanced volume to capacity (V/C), or excess green to arterial with the minor street at level of service C] make a significant difference?

All of these questions were to be answered for each of six MOEs and two levels of aggregation (arterial and networkwide). The MOEs were delay; stops; fuel consumption; and hydrocarbon (HC), carbon monoxide (CO), and oxides of nitrogen (NO_x) emissions. All signal-timing-control parameters were independent variables.

Figure 5 shows the 60-cell experimental design matrix for the manually developed signal-timing plans. These timing plans were also used as the initial timings for the TRANSYT model. The TRANSYT model then generated optimal timing plans that minimized the following performance index:

$$PI = \sum_{\text{all links}} (\text{total delay}) + K \sum_{\text{all links}} (\text{number of stops}) \qquad (1)$$

where PI is the performance index and K is a stop weighting factor.

Figure 6 illustrates the resulting 30-cell experimental design matrix for the TRANSYT timing plans. NETSIM evaluations were conducted by using one replication per cell, each replication being a simulation of a 15-min time period. Due to computer time limitations, the NETSIM evaluation of the manually developed timing plans was redesigned as a half-fractional factorial experiment.

The previously described hypotheses regarding the relations among the timing plans, the performance measures, and the evaluation models were tested by using ANOVA techniques. Performance data were aggregated at two levels: arterial links only and the overall network. The presence of interactions between variables and then the main effects of all factors were investigated. A multiple comparison of whether treatment (variable) means differed significantly was conducted after the ANOVA. These comparisons were made by testing the significance of particular linear combinations of the variable means. The procedure used was Duncan's multiple range test with a 0.01 significance level.

CALIBRATION OF TRANSYT AND NETSIM

Prior to the use of the TRANSYT6C and NETSIM computer models, a number of test runs were made for the existing evening peak-hour signal timing to calibrate those program-embedded parameters that showed significant differences from observed values. This procedure also provided a means of validating the results of selected experiments through actual field measurements. The model calibrations were primarily concerned with the following parameters: start-up delay, lag, stop estimate, saturation flow rate, free-flow speed, and amber phase response. The Wilcoxon matched-pairs signed-ranks test was used, and no significant difference was found between the TRANSYT, NETSIM, and field-observed values for the six selected traffic performance measures.

Because of the differences in the way each model defines a link connecting two intersections, as well as the way in which performance statistics are accumulated, special procedures had to be followed to ensure consistency in the comparisons of TRANSYT and NETSIM output. In TRANSYT, the delays actually incurred at the beginning of a receiving link and at the end of an approaching link are aggregated and assigned to the upstream link. This includes all through and left- and right-turning movements. For this reason, the TRANSYT network does not use exit links. On the other hand, in the NETSIM model, the link statistics are associated with the aggregate performance of all vehicles traveling from and to the respective stop lines that define the two ends of the link.

Since an internal link for both models encompasses some acceleration and deceleration delay, the accumulated statistics for the two models are not significantly different. For entry links, however, the difference between the two models is significant because the TRANSYT entry link includes both acceleration and deceleration delay at the stop line whereas the NETSIM entry link excludes the acceleration delay at that stop line. As a result, the flow statistics for TRANSYT entry links are usually much higher than those for NETSIM. Therefore, for the NETSIM and TRANSYT models to be consistent, the NETSIM network was coded with exit links that would account for the acceleration delays incurred in departing the stop lines of exit nodes.

A special adjustment to the TRANSYT output was also necessary in the calculation of the average speed on a link or for the overall network. For internal links, the average travel speed is obtained by dividing the distance traveled by the time spent on the link. Here, the time spent represents an actual travel time, including travel time for free-flow speed, and uniform and random delay. However, the program ignores the travel time on the entry link. Therefore, the time spent on the entry link is equivalent to the uniform plus random delays incurred in a queue. Consequently, average travel speed cannot be calculated from the data for distance traveled and time spent on the entry link. For the same reason, the networkwide average travel speed cannot be obtained by dividing the total distance traveled by the total time spent for the network as a whole. Therefore, for the purpose of comparing TRANSYT and NETSIM with respect to travel time and average speed, the TRANSYT output was adjusted by adding a reasonably estimated travel time to the uniform and random delay on each entry link. The additional time spent for each entry link in the TRANSYT output was calculated by multiplying the flow rate by its link length and then dividing by an average cruising speed observed in the field.

FINDINGS

The experimental design involved four basic experiments:

1. TRANSYT evaluation of manual timing plans,
2. TRANSYT evaluation of TRANSYT-optimized timing plans,
3. NETSIM evaluation of manual timing plans, and
4. NETSIM evaluation of TRANSYT-optimized timing plans.

Pairs of experiments were then coupled together to become a module for purposes of statistical and graphical comparison. The results of these comparisons are summarized below.

Traffic-Signal Parameters Versus MOEs

No interactions existed among the traffic-signal parameters. Each level of a traffic-signal parameter had a response curve that showed the same trend against each level of the other traffic-signal parameters. For example, total delay over each cycle length for K = 5 had the same trend as for K = 60 or 90, which showed that no interaction existed between K-factor and cycle length.

The principal results derived from the individual experimental analyses for the case-study site are summarized in Table 1 and discussed below:

1. Signal cycle length always had the most significant effect on each of the MOEs. Within the range of 80- to 140-s cycle lengths, delay, fuel consumption, and HC and CO emissions remained relatively constant. However, number of stops and NO_x emissions decreased as cycle length increased. The greatest inefficiencies for all MOEs occurred at the 60-s cycle length. This was due principally to the fact that, at cycle lengths less than or equal to 80 s, the minor streets received more green than necessary because of the minimum green interval constraint for accommodating pedestrians.
2. The stop weighting factor (K) used in the TRANSYT optimization model was the second most significant variable in terms of delay, stops, and fuel consumption. However, it had no significant effect on vehicle emissions. The number of stops and the amount of fuel consumption decreased as the K-value increased. However, delay in the overall network increased as the K-value increased, whereas delay on arterial links decreased. This is because of the trade-off between the delay to cross-street traffic and the delay to arterial traffic. The study results offered no evidence to support the reported hypothesis (2) that a K-value of 60 would provide a minimum fuel-consumption timing plan. Even though this study showed that a K-value of 90 yields the minimum fuel-consumption timing plan, this result is not sufficient to justify the conclusion that this would occur in every situation.
3. Speed of progression, as used in the manual signal-timing method, was the third most influential variable. It had a significant effect on total delay and number of stops. However, it also had some effect on fuel and vehicle emissions. The higher speeds of progression produced the lower MOE values.
4. Priority policy, as used in the manual signal-timing method, had a greater effect than the split method, but the significance of both variables was considered to be negligible. Usually the "peak-direction priority" and "excess green time to arterial" options would slightly reduce the delay to arterial traffic. The other MOEs were also reduced by using the peak-direction-priority option.

Manual Versus Optimized Timing Plans

In general, TRANSYT-optimized timing plans were found to improve all MOEs both on the arterial links

Table 1. Summary of interactions between signal-timing parameters and MOEs.

Timing Method	Parameter	Total Delay	Stops	Fuel Consumption	Emissions		
					HC	CO	NO_x
Manual	Cycle length	⊕	⊕	⊕	⊕	⊕	⊕
	Speed of progression	+	⊕	+	+	+	+
	Priority policy	+	+	+	+	+	+
	Split method	+					
TRANSYT	Cycle length	⊕	⊕	⊕	⊕	⊕	⊕
	K-factor	⊕	⊕	⊕			
	Priority policy				+		

Note: + = main effect detected from TRANSYT output, and ⊕ = main effect detected from NETSIM output.

Table 2. Relative benefits of optimized timing plans: average percentage improvement at 120-s cycle length.

Area	Total Delay (%)	No. of Stops (%)	Fuel Consumption (%)	Emissions (%)		
				HC	CO	NO_x
Arterial	22	25	5	6	12	2
Network	13	20	4	4	6	2

Table 3. Average percentage difference in MOEs from TRANSYT and NETSIM models at 120-s cycle length.

Area	Total Delay (%)	No. of Stops (%)	Fuel Consumption (%)	Emissions (%)		
				HC	CO	NO_x
Arterial	38	18	17	-22	17	60
Network	17	14	14	-33	7	58

and the overall network, especially in the range of 80- to 140-s cycle lengths. The improvement of the optimized timings versus the manual timing plans increased as signal cycle length increased. The number of stops and total delay showed the most change; fuel consumption and vehicle emissions were less sensitive to the timing methods.

For example, Table 2 gives the improvements found for a 120-s cycle length. The percentage differences given in the table were computed from NETSIM simulation data and represent the relative improvement of the optimized timing plans with respect to the manually developed timing plans. The ability of the TRANSYT model to generate improved signal-timing plans compared with traditional methods has, of course, been noted and reported before.

TRANSYT Versus NETSIM

Except for the 60-s cycle lengths, the MOEs estimated by the two models were found to vary in a similar manner as cycle length ranged from 80 to 140 s and the NETSIM model was found to produce the larger MOE values. At the 60-s cycle length, almost all arterial links were oversaturated. Under these conditions, TRANSYT was found to generate very large delay estimates compared with NETSIM. The average difference in the MOEs estimated by the two models increased as signal cycle length increased within the range of 80-140 s. Average differences between the MOEs evaluated by the two models are given in Table 3 for a 120-s cycle length.

Except for HC emissions, all MOEs estimated by NETSIM have larger values than those produced by TRANSYT. The particularly large difference in delay for the arterial links may be caused in part by the difference in definition of the TRANSYT link and the NETSIM link. Because the MOEs estimated by the NETSIM model account for not only signal-related effects but also midblock interference, the NETSIM model should produce higher values for the MOEs. The models also differ in their estimates of fuel consumption and vehicle emissions. These differences are probably due in large part to the nature of the fuel-consumption and emissions subroutines within each model.

The difference between the TRANSYT and NETSIM models for the various MOEs might also be attributed to some extent to the error caused by having only one NETSIM run for each cell of the experimental design matrices. The NETSIM user's manual suggests at least two replications for each cell. A limited number of test runs conducted by using different random seeds for one of the cells showed a range in total network delay of approximately 7 percent and a slightly higher percentage for arterial delay. The range of total delay is almost the same size as the previously determined percentage change in the MOE due to the use of different K-factors but far less than that due to the model used.

Relations among MOEs

Possible relations among the various MOEs were of interest because this information would indicate whether one MOE could be used as a surrogate indicator for the others. Because cycle length was shown as the dominant signal-timing parameter, a comparison of each MOE over cycle length was made to reveal any correlation or similar response pattern among MOEs.

Figure 7 shows the relation over cycle length of various network MOEs as evaluated by the TRANSYT model. As shown in the figure, total delay, fuel consumption, and HC, CO, and total pollutants (combination of HC, CO, and NO_x) fall into a category that shows the same response pattern over cycle length. However, number of stops and NO_x emissions fall into another category that shows a steady decrease in the MOE as the cycle length increases. Figure 8 shows similar relations between cycle length and network MOEs evaluated by the NETSIM model.

Table 4 gives regression equations developed from the data in Figures 7 and 8. From the correlation coefficients for the NETSIM data, it is apparent that total delay is strongly associated with fuel consumption and HC, CO, and total emissions. The high correlation between total delay and fuel consumption implicitly supports the finding reported by Cohen and Euler (5) in their study of an isolated intersection: that delay and fuel consumption are minimized at approximately the same cycle length. Of the individual pollutants, only NO_x emissions were found to be well associated with number of stops. Fuel consumption and total delay were both reasonably well correlated with number of stops.

CONCLUSIONS

At the outset of the research, there were several fundamental questions to be resolved. The conclu-

Figure 7. Relation among network MOEs generated by TRANSYT.

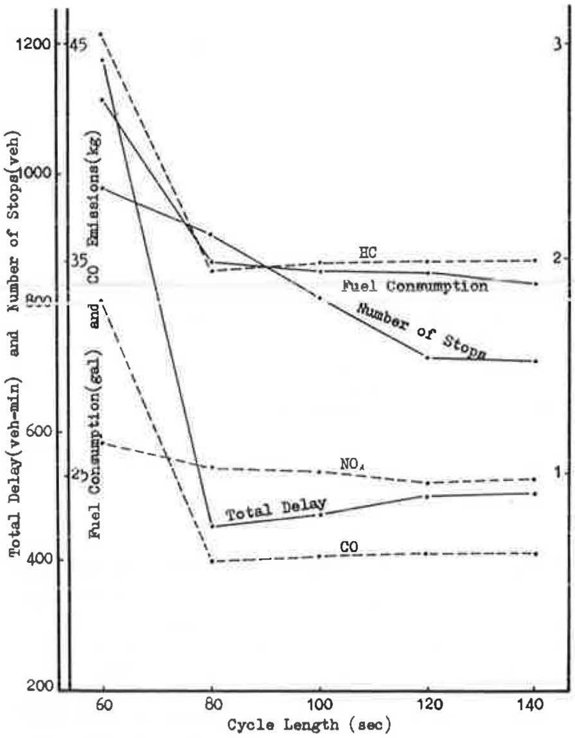


Figure 8. Relation among network MOEs generated by NETSIM.

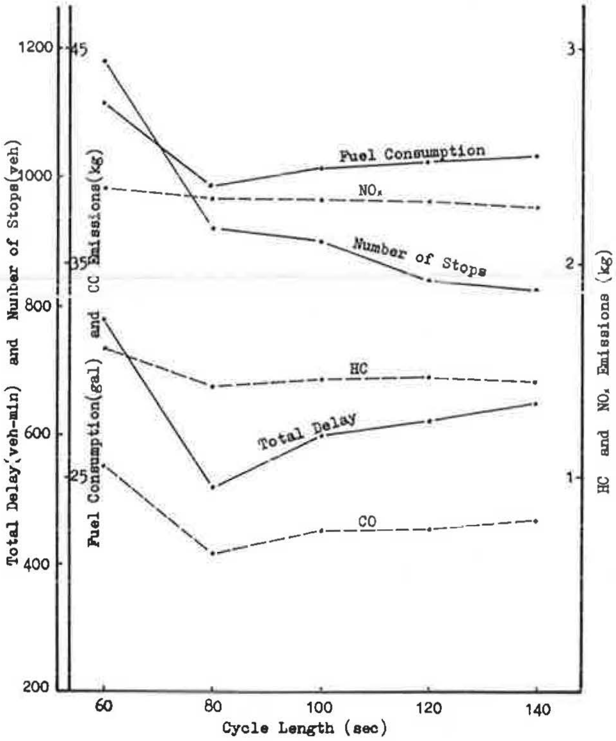


Table 4. Regression equations for relations among MOEs in network.

	TRANSYT		NETSIM	
MOEs	Equation	Correlation Coefficient	Equation	Correlation Coefficient
FC versus TD	FC = 28.9 + 0.012TD	0.973	FC = 30.8 + 0.015TD	0.958
HC versus TD	HC = 1212 + 1.6TD	0.998	HC = 1080 + 0.64TD	0.906
CO versus TD	CO = 12 530 + 18TD	0.997	CO = 13 945 + 14.4TD	0.976
TP versus TD	TP = 14 633 + 19.8TD	0.996	TP = 17 220 + 15.2TD	0.970
HC versus NS	HC = 1190 + 1.21NS	0.524	HC = 1183 + 0.33NS	0.766
NO_x versus NS	NO_x = 651 + 0.46NS	0.939	NO_x = 2090 + 0.22NS	0.743
TP versus NS	TP = 13 530 + 16NS	0.559	TP = 20 390 + 7NS	0.739
TD versus NS	TD = 31 + 0.7NS	0.488	TD = 308 + 0.35NS	0.584
FC versus NS	FC = 27.26 + 0.011NS	0.615	FC = 33.7 + 0.007NS	0.755

Note: FC = fuel consumption (gal), TD = total delay (vehicle-min), HC = hydrocarbon emissions (g), CO = carbon monoxide emissions (g), TP = total pollutant emissions (g), NS = number of stops (vehicles), and NO_x = nitrogen oxide emissions (g).

sions that can be drawn with respect to these questions are summarized below:

1. Among the various signal-timing parameters, cycle length and K-factor in the TRANSYT performance index are the most significant variables that affect the MOEs. However, the study failed to identify an optimal value of K that would produce a minimum level for each MOE. Speed of progression is highly correlated with number of stops: A higher value yields a lower number of stops. Priority policy and split method did not show a significant impact on any of the MOEs.
2. All MOEs can be improved, especially stops and delay on the arterial links, when optimized timing plans are used instead of those developed by use of traditional time-space diagram methods.
3. When the TRANSYT6C and NETSIM simulation models are compared, the NETSIM model produces similar, but larger, values for the MOEs under a given signal-timing plan. This is probably due simply to the differing simulation logic within the two models.
4. There appeared to be many correlations or similar response patterns among the various MOEs. Number of stops and NO_x emissions showed a close correlation, whereas delay appeared to be a strong surrogate for the other principal MOEs.

Because the study was performed for a single case-study site that had a unique set of traffic flows, it is unknown whether different traffic and roadway conditions would lead to significantly different results. In addition, the results of this study were limited in that it was only possible to conduct one replication for the cells of the experimental design matrices. This could create a large source of error or a loss in the power of the tests. Therefore, further research could be focused on multiple replications of other scenarios with different roadway and traffic conditions.

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