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Signal Cycle Length and Fuel Consumption and Emissions

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A microscopic network simulation model (NETSIM, formerly UTCS-1) was used to evaluate the relationship between fuel consumption and signal cycle length. A single intersection was simulated for three scenarios having different traffic characteristics. It was found that the cycle length that minimizes delay also minimizes fuel consumption and hydrocarbon and carbon monoxide emissions. A regression analysis showed that fuel consumption and these emissions are strongly correlated with vehicle average speed but that the relationship is not linear. Differences between the results in this work and previous results are discussed.

Since the passage of the Clean Air Act of 1970 and the oil embargo crisis of 1973, the issues of automobile fuel consumption and emissions have greatly increased in importance. Thus, it has been proposed that more emphasis be placed on the measures of effectiveness (MOEs) for fuel consumption and emissions and on such traditional measures as speed, stops, and delay. Thus, various types of policies affecting traffic flow would be evaluated as to their effect on the fuel-emission MOEs, speed, and so forth.

In recent years a number of authors (1, 2, 3, 4, 5, 6, 7) have addressed themselves to the issue of fuel consumption in urban traffic. Bauer (1) and Courage and Parapar (2) investigated the relationship between signal cycle length and fuel consumption. Lieberman and Cohen (3) and Honeywell (4) addressed the issue of finding the effects of different traffic control strategies on fuel efficiency (measured in distance traveled versus fuel consumed). Evans, Herman, and Laur (5) addressed the problem of relating fuel consumption to other traffic MOEs such as average speed, while Pattersen (6) and Cohen (7) examined the problem of estimating the concentration profile of traffic-generated carbon monoxide at signalized intersections.

Of particular interest are the findings of Bauer (1) and Courage and Parapar (2). The analysis performed by these authors showed that at an isolated intersection the cycle length at which fuel consumption is minimized is very much longer than the cycle length at which delay is minimized.

In the present study, we shall describe an analysis of this finding that was conducted using the network flow simulation [NETSIM, (8), formerly the UTCS-1] model. Our result differed from others (1, 2) in that fuel consumption and the hydrocarbon (HC) and carbon monoxide (CO) emissions were found to be minimized at approximately the same cycle length as delay. Another finding of interest was that MOE stops did not always follow Webster's expression (9, 10), which predicts that number of stops decreases as the cycle length increases.

A regression analysis was performed to examine relationships between the average speed and MOE fuel consumption and emissions. It was found that there is a strong correlation between these measures but that the relationships are not linear.

PROBLEM DESCRIPTION AND TECHNICAL APPROACH

In order to isolate the relationship between signal cycle length and average speed, stops, fuel consumption, and emissions, we confined ourselves to the analysis of single isolated intersections.

The initial configuration involved the analysis of a two-phase pretimed signal. In future work, we plan to analyze more complicated situations, in particular multiphase signals and varying geometric configurations.

Our approach to the problem was to use NETSIM as modified to compute fuel consumption and emissions (4). This approach is particularly appropriate for analyzing fuel versus emissions impacts, because it is difficult to measure the former directly in the field and impossible to measure the latter.

NETSIM is a microscopic network simulation model. Thus, individual vehicle movements are simulated according to car-following, queue discharge, and lane-changing laws. Vehicles are generated on entry links according to a shifted exponential headway law. However, since there is a spread of free-flow speeds and car-following interactions on the network links, the arrival patterns at the rear of the queue will in general be complicated.

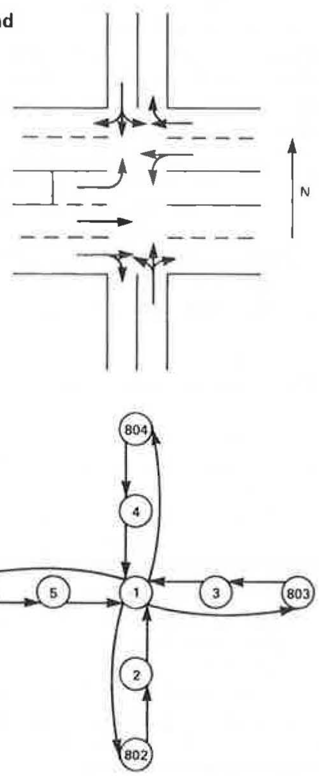
The model has been validated in a network in Washington, D.C., and single intersections in Arlington, Virginia; Berkeley, California; and New Jersey. The model has been used on several projects for a variety of research and operations applications.

DESCRIPTION OF INTERSECTION SCENARIOS

The first intersection examined is shown in Figure 1. Each east-west approach of the intersection was assumed to have two through lanes, with the east-to-north left-turn movement served by a left-turn bay. Each north-south approach of the intersection had one through lane. This configuration provides a considerable amount of geometric variability. All approach lengths were assumed to be 305 m. The assumed free-flow speed on the east-west approach was 64 km/h and 56 km/h on the north-south approach.

Scenarios were generated by varying volume and left- and right-turn percentages on each approach of the intersection. Opposing movements on the same street (for instance, the west-to-east and east-to-west movements) always had equal volumes and turn percentages. Since the opposing volumes only interfere with left-turn movements, there is little loss of generality in imposing this restriction. On the east-west approaches, volumes ranged between 600 vehicles per hour (vph) and 2400 vph in increments of 200 vph. On the north-south approaches, volumes ranged between 300 and 1200 vph in increments of 100 vph. The left- and right-turn movements were either 0, 10, or 20 percent of the total approach volumes and varied by approach. By varying the volume and turning percentage for each approach, a total of 8100 scenarios was generated.

Figure 1. Intersection geometrics and associated link-node diagram.



For each of the generated scenarios, the degree of intersection saturation was first calculated. This is the sum of all phases of the critical approach volume-to-capacity (V/C) ratios for each phase.

$$S_i = V_{i_{crit}}/C_{i_{crit}} \quad (1)$$

where

S_i = degree of saturation of the ith critical approach to the intersection,
$V_{i_{crit}}$ = critical approach volume for the ith phase, and
$C_{i_{crit}}$ = critical approach capacity for the ith phase.

The V/C ratios for both direction movements for both approaches were calculated from the following equation.

$$V/C = V/(NC \times \text{Lanes}) \quad (2)$$

where

NC = nominal capacity = (3600 s/h)/(2.4 s/vehicle) and
Lanes = number of lanes serving through traffic on the approach.

In the case of an exclusive left-turn lane, this equation was modified to

$$V/C = [V(1.0 - LT)]/(NC \times \text{Lanes}) \quad (3)$$

where LT is the fraction of left turns.

The minimum-delay cycle length for each scenario was then estimated by using Webster's formula as

$$C = [1.5(L) + 5]/(1 - S) \quad (4)$$

where

C = cycle length,
$S = \sum_i S_i$, and
L = total lost time, assumed to be 4 s, on the critical approaches.

Oversaturated intersections (S > 1) were eliminated from consideration, since these would have no minimum-delay cycle lengths. All scenarios were executed by varying the cycle lengths in 20-s intervals between 40 and 150 s. These limits were chosen to correspond to cycle lengths used in practice on two-phase signals. From these runs, the cycle length giving the lowest delay for each scenario was determined. Two further runs for each scenario were made at 10-s cycle length intervals around this value to further refine the results. The green split for each of these scenarios was calculated from Webster's demand relation as

$$g_i = S_i/S \quad (5)$$

where g_i is the proportion of green time of the ith phase.

The green splits were held constant for all cycle lengths listed for a given scenario.

The research plan was to execute several scenarios that would be chosen to provide a wide range of volume and turning movement conditions. Results of runs of the first three of these are described in Table 1 and reported in this work.

For each scenario and cycle-length pair, ten replications of a half-hour period were simulated. The effect of varying the cycle length at the intersection can then be examined for a series of measures: average delay in seconds per vehicle, average speed in kilometers per hour, number of stops per vehicle, fuel efficiency in kilometers per liter for the intersection, and emissions of hydrocarbons, carbon monoxide, and oxides of nitrogen in grams per kilometer for the intersection.

The measures described above are computed in NETSIM as follows.

1. Average speed is calculated by dividing the total number of vehicle kilometers traveled on each link by the total number of vehicle hours spent on the link.
2. Average delay is calculated by subtracting the number of vehicle seconds that unimpeded vehicles would spend on a link from the actual number of vehicle seconds spent on a link and then dividing by the total number of vehicles discharged from the link.
3. Stops are the number of simulated vehicles that are forced to stop by traffic conditions.
4. Fuel emissions are assessed, by a table of fuel-emissions rates, for each second by each vehicle using the vehicle's speed-acceleration couplet (8).

RESULTS

Cycle Lengths

The results of the three scenarios are shown in Figures 2-7. Figure 2 is a plot of average delay versus cycle length; Figure 3 shows fuel consumption versus cycle length; Figure 4 shows stops versus cycle length; Figure 5 shows HC versus cycle length; Figure 6 shows CO versus cycle length; and Figure 7 shows NOX versus cycle length. The plotted points are averages over the ten replications run for each scenario.

It can be seen that, in all three cases, the cycle length at which minimum delay occurs is the cycle length where minimum fuel consumption and HC and CO emissions occur. This is approximately 60 s for scenario 463, 80 s for scenario 1462, and 100 s for scenario 3836. This result differs from those obtained elsewhere (1, 2). A discussion of the reasons for this follows shortly.

We also observe that stops are minimized at 60 and 80 s for scenarios 463 and 1462, respectively, while the stops curve for scenario 3836 decreased as a function of cycle length.

These findings on stops may be demand dependent, because the V/C ratios on the critical approaches are higher in scenario 3836.

Regression Analyses

The object of this exercise was to examine the correlation between average speed and the MOE's fuel consumption and emissions.

Average speed was chosen because it was a tested independent variable (4, 5). First and second order regressions were run. Since a total of 26 cycle lengths over the three scenarios was tested by executing ten replications for each cycle length and there were four intersection approaches, there was a total of 1040 data points. These points are plotted in Figures 8-11.

The results for fuel consumption and HC and CO emissions showed a very high correlation between these measures and average speed. In all three cases, the second order terms were found to be significant. In addition, HC and CO were regressed against 1.00/average speed. The regression lines were

$$FC = 0.695 + 0.471*(\text{average speed}) - 0.0154*(\text{average speed})^2 \quad (6)$$

Table 1. Scenario parameter descriptions.

Scenario No.	Phase I (east-west) Vol.	Phase I Percentage Left Turns	Phase I Percentage Right Turns	Phase II (north-south) Vol.	Phase II Percentage Left Turns	Phase II Percentage Right Turns	$GS(G_1/G_2)$	Minimum Delay Cycle[a]
463	1600	0	0	500	0	10	1.525	60
1462	1800	0	10	400	0	20	2.143	80
3836	1000	10	10	800	10	20	0.608	100

[a] Determined from the NETSIM simulation model.

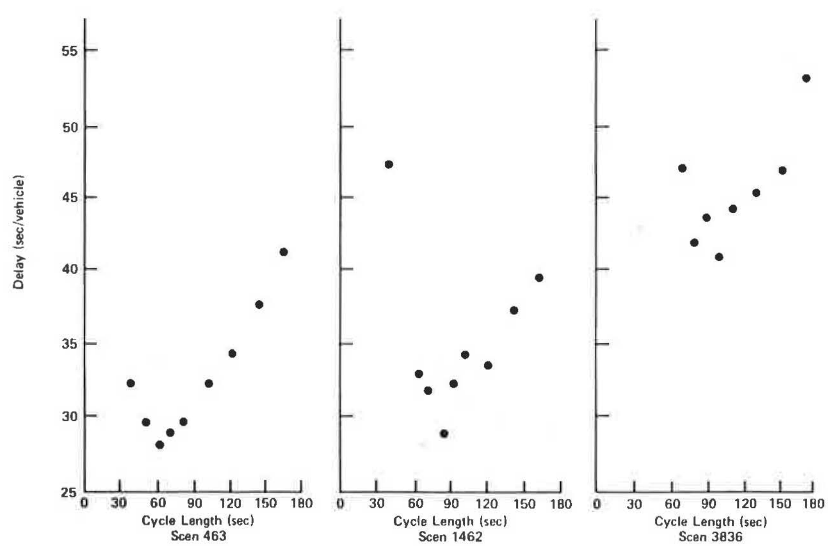


Figure 2. Plot of delay versus cycle length for three scenarios.

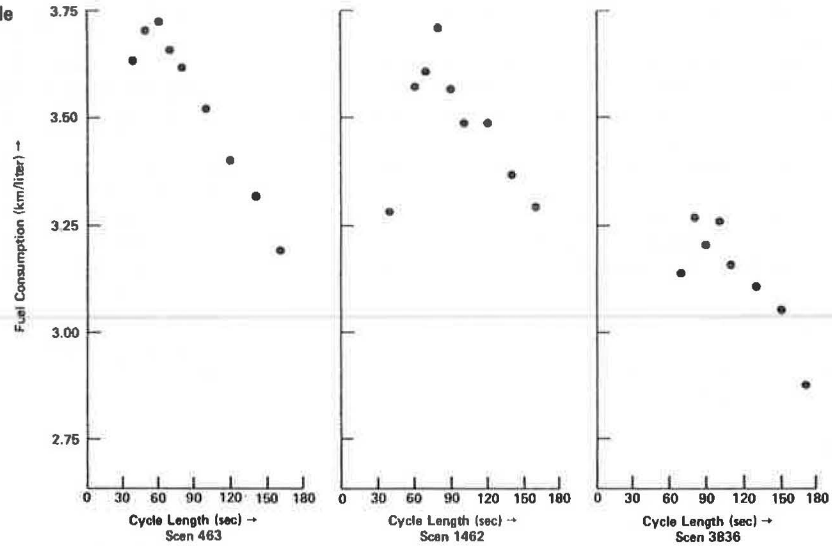


Figure 3. Plot of fuel consumption versus cycle length for three scenarios.

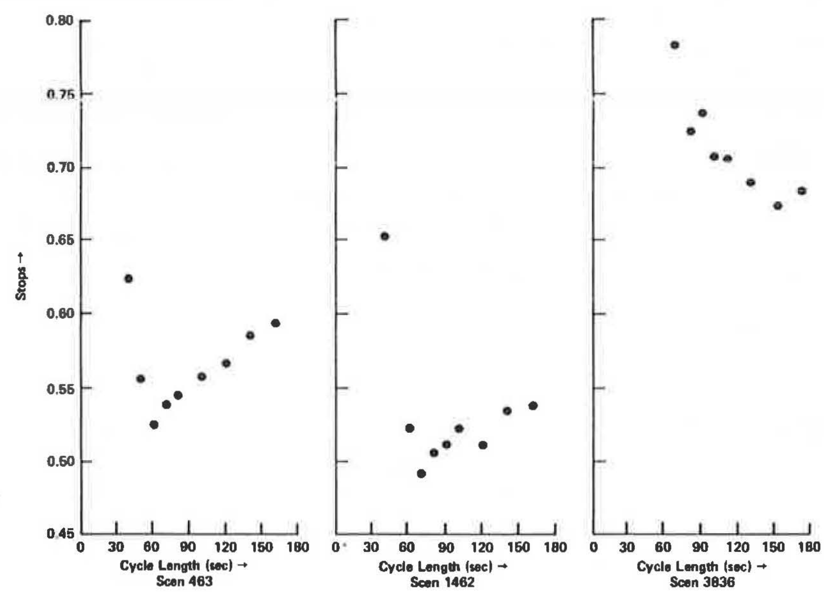


Figure 4. Plot of stops versus cycle length for three scenarios.

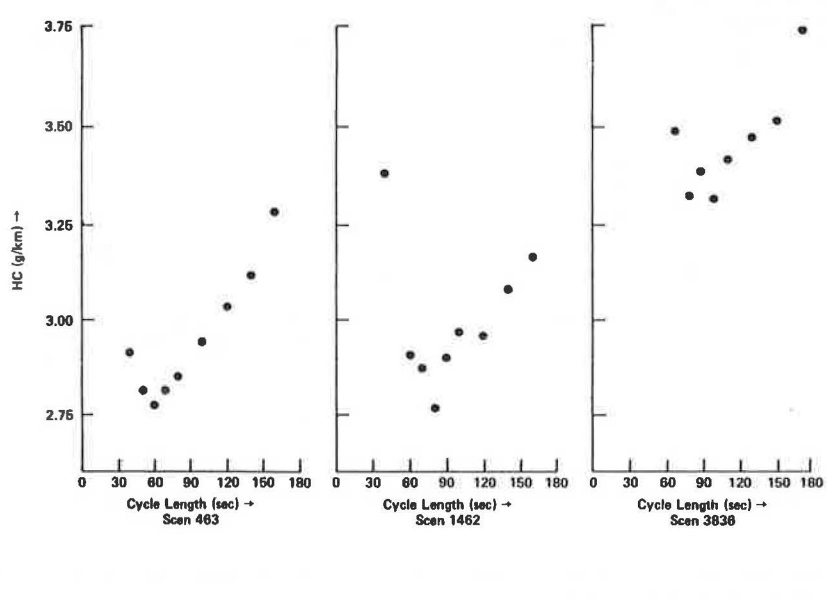


Figure 5. Plot of HC emissions versus cycle length for three scenarios.

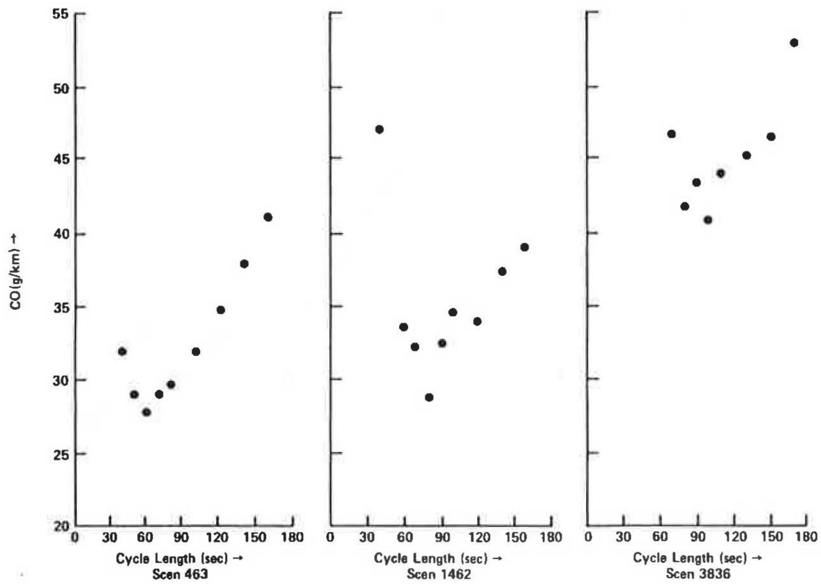


Figure 6. Plot of CO emissions versus cycle length for three scenarios.

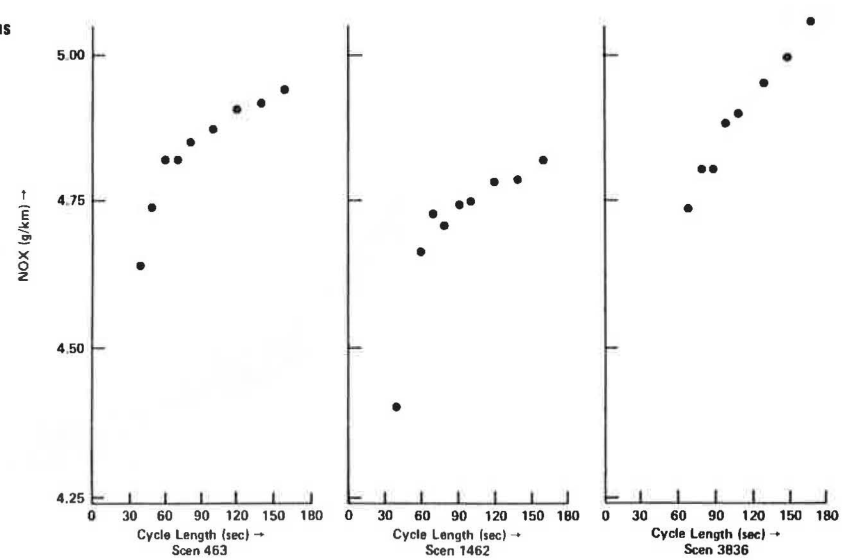


Figure 7. Plot of NOX emissions versus cycle length for three scenarios.

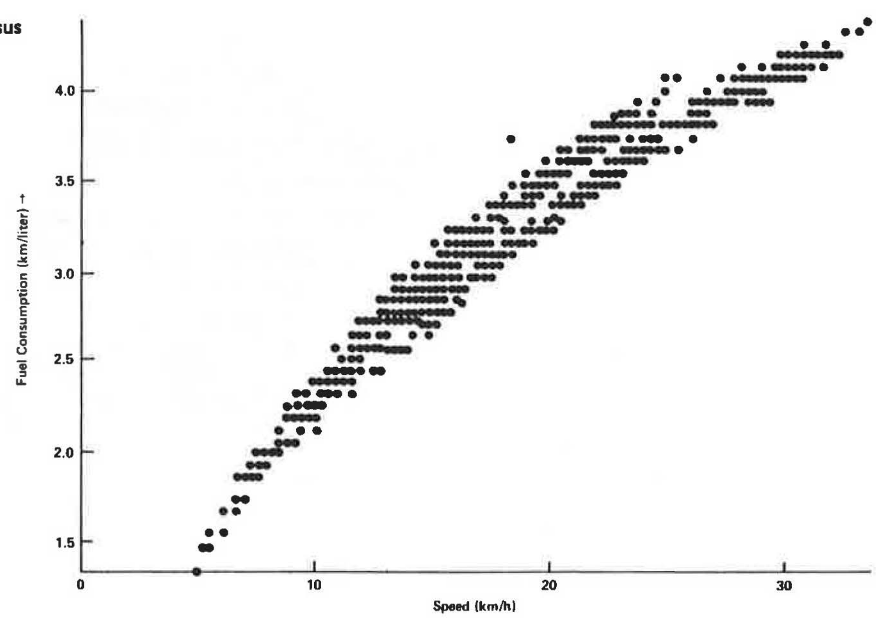


Figure 8. Plot of fuel consumption versus average speed.

Figure 9. Plot of HC emissions versus average speed.

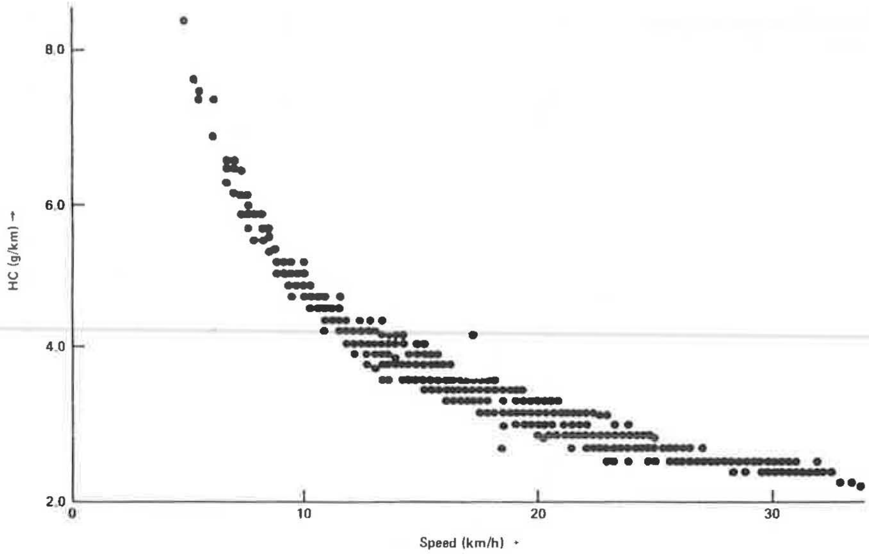


Figure 10. Plot of CO emissions versus average speed.

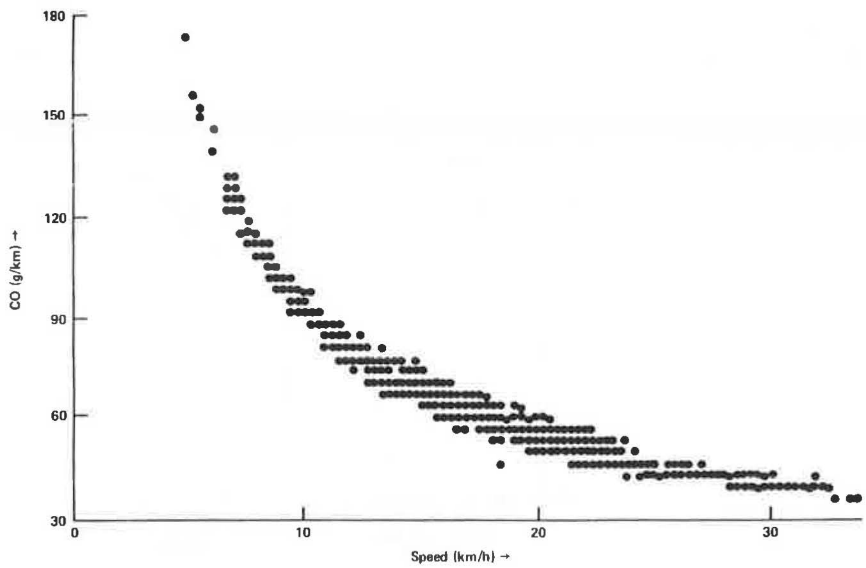
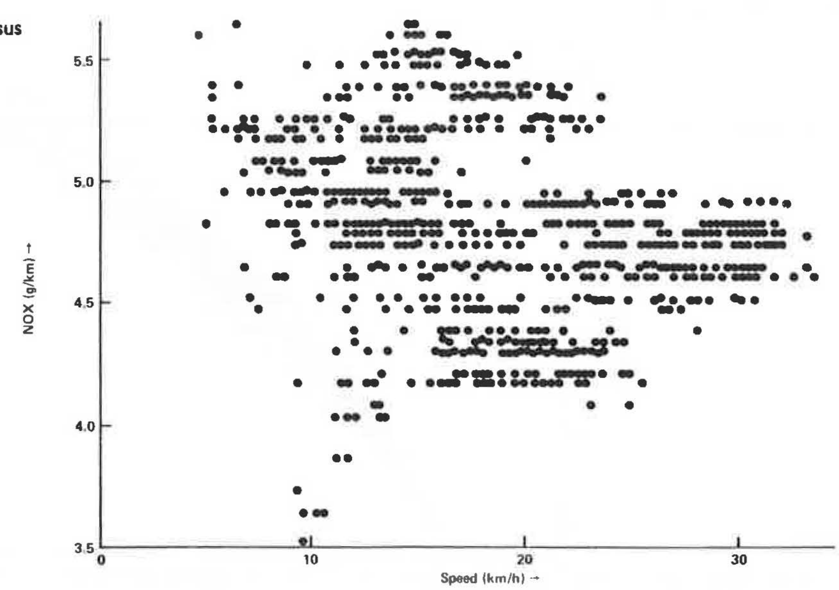


Figure 11. Plot of NOX emissions versus average speed.



for fuel consumption in kilometers per liter versus average speed in kilometers per hour ($R^2 = 0.975$);

$$HC = 8.342 - 1.065*(\text{average speed}) + 0.0483*(\text{average speed})^2 \quad (7)$$

for HC emissions in grams per kilometer ($R^2 = 0.9266$) or, alternatively,

$$HC = 1.36 + 21.46*(\text{average speed}) \quad (8)$$

($R^2 = 0.964$);

$$CO = 171.71 - 23.87*(\text{average speed}) + 0.096*(\text{average speed})^2 \quad (9)$$

for CO emissions in grams per kilometer ($R^2 = 0.934$) or, alternatively,

$$CO = (16.03 + 476.1)/(\text{average speed}) \quad (10)$$

($R^2 = 0.970$). No correlation was found between NOX and average speed.

CONCLUSIONS

The results to date of this study, which are admittedly somewhat limited, indicate that the cycle length, which minimizes delay at an isolated intersection, also minimizes fuel consumption and the emittants HC and CO.

Fuel consumption and emissions are strongly correlated with average speed, but the regression relation is not linear.

Stops appear to play no role in the analysis, probably because they are correlated closely with delay (11).

Great care must be exercised in applying regression relations such as those found in this work. The expressions we used should not be used in situations in which average speeds greater than 30 km/h occur. This was the highest speed occurring in this study, and it is unwise to extrapolate using such regressions. The fuel consumption and emission figures derived here are based on a particular vehicle mix (3). It is rather unlikely that different vehicle mixes (possibly involving trucks as well as cars) would lead to the same regression parameters. It should be noted that the regression relationships derived here are based on link-wide results aggregated over all vehicles that traversed the link. The result obtained by Evans, Herman, and Laur (5) was based on a set of floating car runs. These relationships were determined from an analysis of a single isolated intersection with a two-phase signal. The results of the regressions do not necessarily apply to other situations.

The inverse relationship between average speed and HC and CO emissions is probably better than the quadratic, as there is evidence that these emittants level out at higher speeds, and the correlation coefficients are better.

Future research in this area will be aimed at running several more scenarios on this geometric configuration and examining the effects of multiphasing and other geometric configurations and generating data at higher average speeds in order to improve the range of validity of the regression relations.

DISCUSSION

There are several reasons that probably account for the discrepancy between this work and others (1, 2). The fuel consumption increment due to cars that slow down but do not stop is not considered. Since NETSIM is microscopic, this effect is automatically included. It is assumed (1, 2) that all stop cycles are the same. This is generally not true, as the acceleration pattern from the locked wheels position is a function of queue position. Thus, the first vehicle in a queue accelerates directly up to cruising speed, while 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 is usually more costly in fuel than traveling at the cruise speed. Again, the microscopic queue discharge behavior of NETSIM automatically includes this effect. The effect of multiple stops due to left turns is ignored (1, 2). Again, the microscopic logic of NETSIM automatically accounts for this effect.

The major reason why this work is at variance with Webster (9) on the issue of stops versus cycle length is probably due to the different assumptions, such as constant arrivals and departures, in his model. NETSIM has random arrivals and departures.

FIELD DATA VERIFICATION

At the present time, there are no field data that directly support either the conclusions of this work or others (1, 2). There are, however, two field studies that indirectly support our conclusions.

Our finding of a strong correlation between fuel consumption and average speed is in agreement with the finding of Evans, Herman, and Laur (5). This provides a verification of the simulation model results. The other study of relevance was one of traffic delay at signalized intersections performed for the Federal Highway Administration by JHK and Associates (11). Intersection delay and number of vehicles stopping were measured at several signalized intersections for a wide variety of volume and turning movement and geometric situations. It was found that the measures of stops and delay were strongly correlated with each other. This result supports the conclusion that stops do not enter into fuel regression relationships independently of delay.

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Traffic Conflicts as a Diagnostic Tool in Highway Safety

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Accident repeatability from one year to the next was found to be high at 60 intersections (r = 0.64) and 170 spot locations (r = 0.59). Nearly half of the 209 Kentucky locations designated as hazardous by accident criteria were found to have been so identified falsely because of random accident occurrences. Conflict counts were conducted at 5 intersections in central Kentucky to determine characteristics of conflict data. Good reliability was found between observers in simultaneous counts of conflicts and weaves with r values as high as 0.93. Traffic volumes accounted for only about 30 percent of the variation in numbers of conflicts. Reductions in conflicts and accidents that resulted from such safety improvements as installing left-turn signal phasing, raised pavement markers, and green-extension systems at numerous locations were determined. A revised procedure for collecting and utilizing conflict data was described.

Traffic conflicts are measures of accident potential and operational problems at a highway location. Many highway agencies are now using traffic conflict techniques to complement the limited accident data found in accident records. The Kentucky Department of Transportation has used various forms of conflict data since 1972 to assist in its efforts for highway improvement. While new procedures are currently under development for collection and use of conflict data in Kentucky, past experiences with conflicts have proved very encouraging.

The first formalized procedure for identifying and recording traffic conflicts at intersections was developed by Perkins and Harris of General Motors Corporation in 1967 (1). Major types of conflicts at intersections include rear-end, left-turn, cross-traffic, red-light violation, and weave conflicts. Conflict counts may be used to quickly evaluate changes in road design, signing, signalization, and environment. After a location is identified as hazardous, a study of conflict patterns can be used with accident diagrams to gain a more accurate understanding of operational deficiencies and accident causes.

Crude forms of traffic conflict counts to determine appropriate safety improvements have been made since traffic engineers first began making field observations. Formalized traffic conflict techniques give a more objective measure of observed traffic problems and allow for a permanent record of the comparative magnitude of such problems. The use of traffic conflict techniques has to date been primarily limited to intersections. However, conflict procedures for other types of locations are under development.

A more severe form of traffic conflict is an erratic maneuver, which is any sudden, unexpected movement by a vehicle that could cause an accident. An erratic maneuver usually involves only one vehicle's making an unsafe move independently of other vehicles. Such a maneuver may often result in a conflict if another vehicle is forced to brake or weave to avoid it. Poor signing and inadequate geometric design often cause erratic maneuvers.

While traffic conflict counts usually indicate the potential for accidents between two or more vehicles, erratic maneuver counts may also provide information about the potential for single-vehicle accidents.

A near-miss accident is a collision between two or more vehicles barely avoided by a last-second movement or stop. This type of accident is a very severe sort of conflict and is rarely observed at any location compared to other conflicts or erratic maneuvers.

Traffic events may be classified in terms of increasing severity from traffic volume to fatal accidents. The ordering of traffic events by severity is as follows:

1. Traffic volume,
2. Routine conflicts,
3. Moderate conflicts and erratic maneuvers,
4. Severe conflicts or near-miss accidents,
5. Minor collisions (usually not reported),
6. Property damage accidents,
7. Injury accidents, and
8. Fatal accidents.

While accident data provide only the last three levels of traffic events, traffic conflict counts provide the other five, since volume counts are usually made along with conflict counts.

NEED FOR CONFLICT DATA

Several limitations have been observed in the use of accident data alone in traffic safety studies. Accident files only contain records of reported accidents, which comprise only a fraction of the accidents that actually occur. The criteria for accident reporting vary considerably among states. For example, all traffic accidents in Colorado, Nevada, and the District of Columbia by law must be reported; only accidents with injury costs exceeding $400 damage to any one person must be reported in Connecticut. Reporting criteria in other states range between these extremes; the most common reporting criteria are $100 (23 states) and $200 (12 states including Kentucky) (2).