Sensitivity of Fuel-Consumption and Delay Values from Traffic Simulation

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The use of a fuel-consumption model developed by using field measurements obtained previously by Claffey is described. The model, called the modified fuel-consumption model, was derived in a form that is suitable for insertion into the NETSIM computer simulation program. Sensitivity analyses were performed by using the existing NETSIM fuel model and the modified fuel-consumption model. The effect of two headway distributions (uniform and shifted negative exponential) on fuel consumption and delay was tested for a hypothetical isolated intersection and an existing small, open network. The impact of various saturation headway values on delay and fuel consumption was investigated, and the incorporation of grade effects in NETSIM through changes in the saturation headway was evaluated. Significant differences in results were found between the two fuel models, and significant differences in both delay and fuel-consumption estimates were found between the two headway models. It was found that delay and fuel consumption were insensitive to saturation headway values between 2.0 and 2.2 s, but significant differences resulted for low to moderate volumes when saturation headway was increased to 2.4 s. Although gradient effects per se have yet to be developed for inclusion in NETSIM, these effects on saturation headway values and the consequent impacts on delay and fuel consumption were found to be significant only at high volumes for grades between -4 and +4 percent.

Heavy dependence on imported oil and the recent extreme increases in the price of gasoline are responsible for the initiation of plans to retime traffic signals in urban areas so as to minimize fuel consumption rather than delay. Currently, there are two schools of thought on how this may be done. Some investigators have used macroscopic approaches to illustrate that extremely long cycle lengths are necessary to minimize fuel consumption (1,2). Naturally, a delay penalty is incurred with this strategy. Other researchers, using either macroscopic or microscopic approaches, have observed that the cycle length that minimizes delay also minimizes fuel consumption (3-5). Any concerted effort to retime traffic signals to minimize fuel consumption should logically be delayed until basic questions such as this have been resolved. Although this paper does not address this particular problem, it does attempt to provide some degree of insight into the state of the art regarding traffic operations and fuel consumption.

Use of microscopic traffic simulation computer programs has long been considered to be a viable and practical technique for evaluating traffic flow. The alternative--collecting and analyzing field data--is time consuming, expensive, and may in the case of traffic networks be impracticable. A detailed simulation program that predicts fuel consumption with reasonable accuracy could be valuable not only for resolving the basic questions concerning minimization of fuel consumption but also for validating other computer programs more likely to be used by engineers in the field. The network flow simulation (NETSIM) program (6) is an existing program that shows considerable promise for serving as such a baseline. NETSIM was developed primarily for closed-network applications, but it has been validated for isolated intersections (6). The program is capable of simulating both pretimed and actuated control and includes fuel-consumption and emissions data in its output. NETSIM has, in fact, been used in some of the investigations concerning cycle lengths that minimize fuel consumption (3,5). Although the program is broad and comprehensive, the making of general statements based on its output might be premature. Questions exist concerning the impact of certain input variable values, the internal program logic, and fuel consumption and delay. The concerns addressed in this paper are

1. The choice of fuel-consumption model,
2. The effect of the headway-distribution model on fuel consumption and delay,
3. The impact of saturation-headway values on fuel consumption and delay, and
4. The effect of grade on fuel consumption through changes in saturation headway.

The remainder of the paper describes program modifications and analyses that provide insight into these concerns.

DEVELOPMENT OF FUEL-CONSUMPTION MODEL

The fuel-consumption tables used in the current version of the NETSIM program were developed from laboratory-based data obtained for 1971-model-year vehicles (7). These tables provide instantaneous rates of fuel consumption in gallons per 100 000 s as a function of vehicle speed and acceleration. Program flexibility permits, at the user's option, the inclusion of alternative fuel-consumption tables. One set of fuel-consumption data frequently used by analysts is that of Claffey (8). Claffey's data may be an attractive alternative to some, since they were measured in the field rather than in a laboratory. These fuel-consumption data were obtained over a wide range of operating conditions for vehicles of the mid-1960s. One might question whether either the fuel-consumption data currently stored in NETSIM or Claffey's data are appropriate for today's fleet-mix and fuel-consumption characteristics. Although nothing can be said with certainty, two earlier studies indicate that these impacts may be small (9,10).

Claffey's data are not presented in a form that is directly suitable for insertion into the NETSIM program. The data that pertain to this study are given in terms of fuel consumption at constant speed, fuel consumption while idling, and excess fuel consumed during speed-change cycles. Excess fuel consumption during a speed-change cycle is defined as the additional fuel consumed beyond that which would have been required had the vehicle continued at constant speed (without performing the speed-change maneuver).

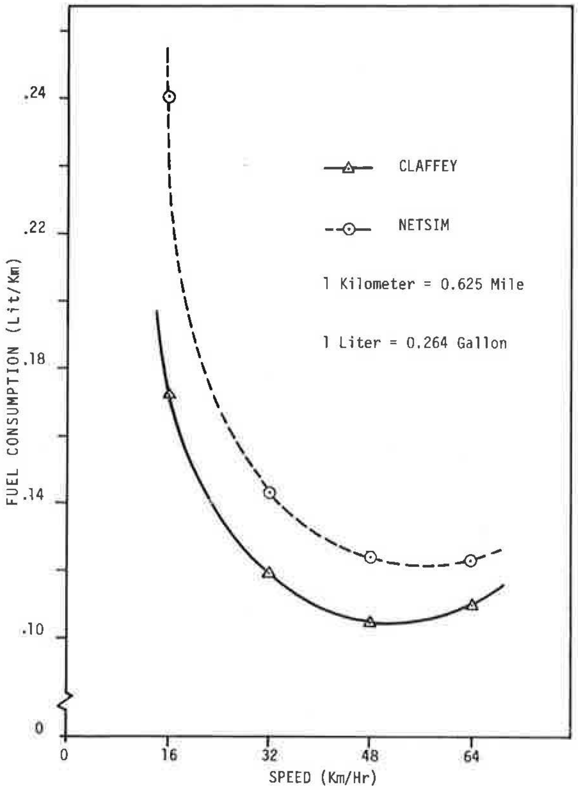
Direct comparisons between Claffey's data base and that of the NETSIM program can be made by converting the NETSIM data to the form used by Claffey. Claffey measured idling fuel consumption at 2.2 L/h (0.58 gal/h) as opposed to the 3.4 L/h (0.90 gal/h) used in NETSIM. The differences in the Claffey and NETSIM data for constant speed at zero grade are shown in Figure 1 for speeds up to 64 km/h (40 miles/h). In order to compare the excess fuel consumed during speed-change cycles, the NETSIM instantaneous consumption rates were integrated over time. This was done for the entire speed-change cycle by using the speed profile that would be generated internally by NETSIM for an isolated vehicle.

A typical NETSIM speed-change profile is shown in

Figure 2. Deceleration takes place at -0.3 m/s^2 (-1 ft/s^2) from some initial speed to 90 percent of the initial speed, followed by deceleration at -2.1 m/s^2 (-7 ft/s^2) to all lower speeds. An acceleration rate of 2.4 m/s^2 (8 ft/s^2) is used for speeds between zero and 3.4 m/s (11 ft/s) and 1.8 m/s^2 (6 ft/s^2) is used for speeds between 3.4 and 5.2 m/s (11 and 17 ft/s). For all speeds greater than 5.2 m/s, the program uses an acceleration rate of 0.9 m/s^2 (3 ft/s^2). The results of these calculations are shown with Claffey's speed-change data in Figure 3. The two data sets exhibit the same general trends, although the differences in magnitudes are relatively large.

To convert Claffey's data to instantaneous consumption rates as required by NETSIM, it was necessary to develop an analytic model that would not only reasonably duplicate Claffey's data but would do so for the NETSIM speed profile. In other words, the task was to develop a model that would enable the NETSIM program to give the "correct" fuel consumption, even though Claffey's tests almost certainly used a somewhat different speed profile. Stepwise regression was used to develop a number of candidate models. Of these candidates, only one model was found that would predict Claffey's data with reasonable accuracy and at the same time show reasonable values and trends for instantaneous fuel consumption. This model is based on the following assumptions:

Figure 1. Fuel-consumption rates at constant speed.



1. The instantaneous fuel-consumption rate is never less than the idling rate.
2. For decelerations less than -0.3 m/s (-1 ft/s), the engine operates at a no-load/no-throttle condition, which results in the instantaneous idling-consumption rate.

For all conditions other than these, the model is given in terms of the NETSIM program units by

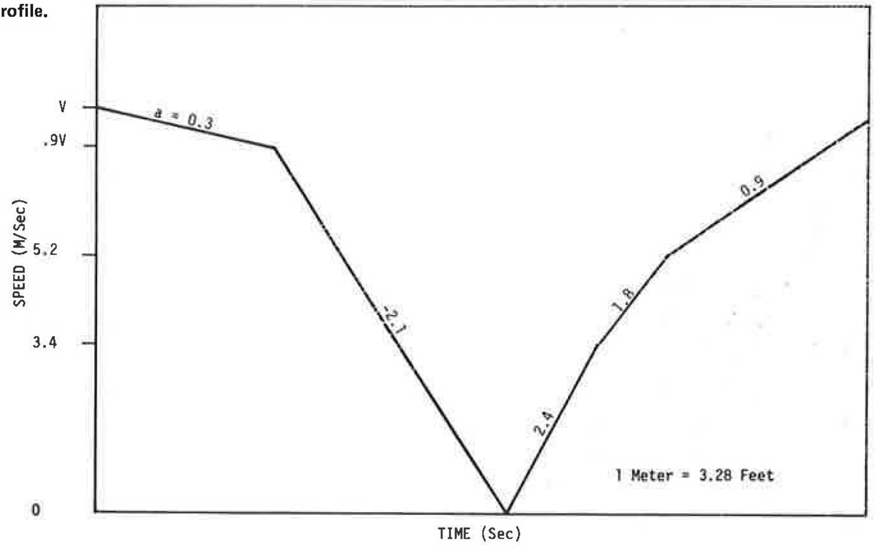
$$g = 16.117 + 0.1658V + 0.007\,252V^2 + 9.626a - 0.009\,577aV^2 + 0.208\,45a^2V \quad (1)$$

where

$\dot{g}$ = instantaneous fuel-consumption rate (gal/100 000 s),
a = instantaneous acceleration rate (ft/s^2), and
V = instantaneous velocity (ft/s).

The implemented model, valid for typical urban speeds only, estimates Claffey's data well for idling, all constant-speed conditions, and all speed-change cycles except for the stop-go speed-change cycle from an initial speed of 16 km/h (10 miles/h). With that exception, the model estimates Claffey's values within 4 percent. A considerably larger error for the 16-km/h stop-go speed-change cycle is possibly caused by the fact that the NETSIM speed profile assumes a higher acceleration rate over most of the acceleration portion of the maneuver than would likely be encountered in practice. In reality, the only time a vehicle is likely to accelerate to a final speed of 16 km/h is when in a queue, and one would not expect

Figure 2. NETSIM speed-change profile.



to observe high acceleration rates under this condition. It should be noted that NETSIM's car-following logic would probably preclude such high values of acceleration being attained in a queue.

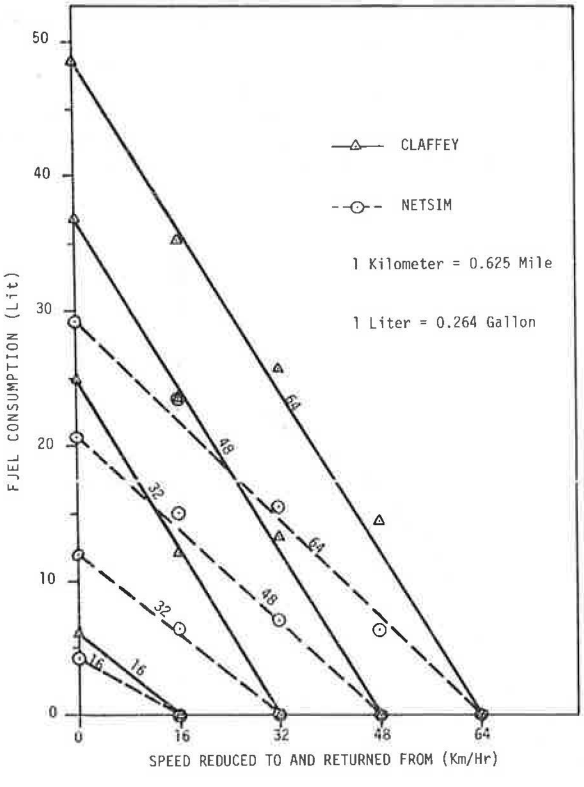
HEADWAY-DISTRIBUTION MODEL

The NETSIM program uses car-following logic to trace individual vehicles through the system. Before car following can take place, however, vehicles are "generated" according to a uniform statistical distribution. This logic for vehicle generation may be reasonable for a large network with high traffic volumes, but it could give inaccurate results for lowto moderate-volume isolated intersections and small networks. NETSIM was modified to generate vehicles according to a shifted-negative-exponential distribution with an assumed minimum headway of 1 s. It is noted that vehicles were generated in this manner in the original version of NETSIM (called UTCS-1).

ANALYSES

Sensitivity analyses were performed with respect to the fuel-consumption model, the headway-distribution model, and values of saturation headway to assess their impact on fuel consumption and delay (saturation headway is defined as the headway corresponding to a saturation flow rate). A hypothetical isolated intersection, shown in Figure 4, was analyzed for a stream that consisted of passenger cars only with no turning movements. Intersection control was assumed to be simple two-phase, pretimed control with a 60-s cycle length and 40 s of green plus amber allocated to the main street for all test cases. The link-node diagram for this hypothetical intersection is shown in Figure 5. To illustrate the magnitudes of the impacts and their variation with demand for an isolated intersection, fixed cross-street demand volumes of 400 vehicles/h and main-street volumes of 600, 1200, and 1800 vehicles/h on each approach were considered. This implies near-saturation conditions on the cross street and approximately 31, 63, and 94 percent saturation on the main street, respectively. It is noted that the degree of saturation for the respective approaches and demands will vary with the saturation headway assumed.

Figure 3. Excess fuel consumed during speed-change cycles.



The impact of the intersection approach gradient on traffic performance has not been extensively studied. An early study by Conley (11) suggested that both negative and positive intersection approach grades decrease starting-time delay and thus increase the saturation flow rate. Dick (12) concluded that the relation between grade and rate of flow was essentially linear and that, for every 1 percent increase (decrease) in grade, saturation flow was reduced (increased) by 3 percent for gradients between -5 and +10 percent. The effects of roadway gradient on traffic operation cannot be directly obtained from a NETSIM simulation exercise, but they can be incorporated in part by changing the

Figure 4. Isolated intersection.

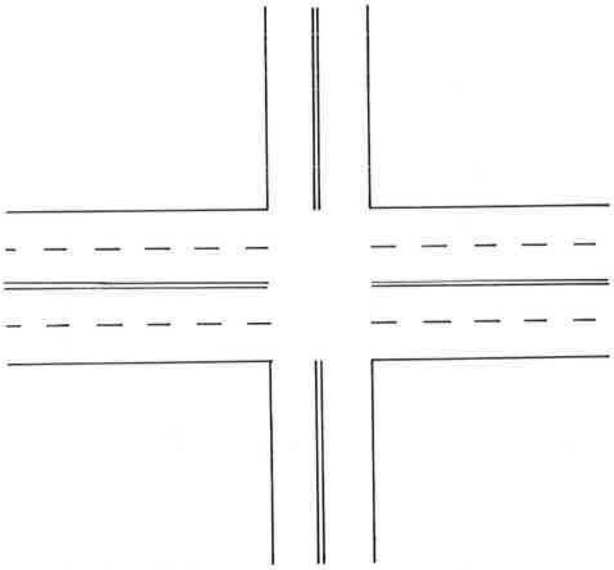


Figure 5. Link-node diagram for intersection.

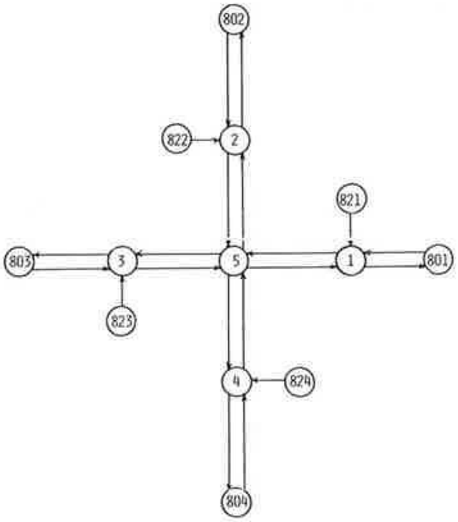
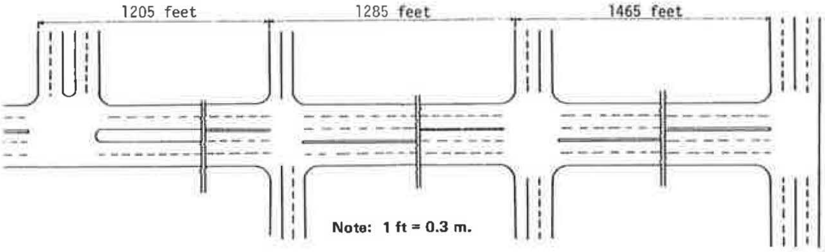


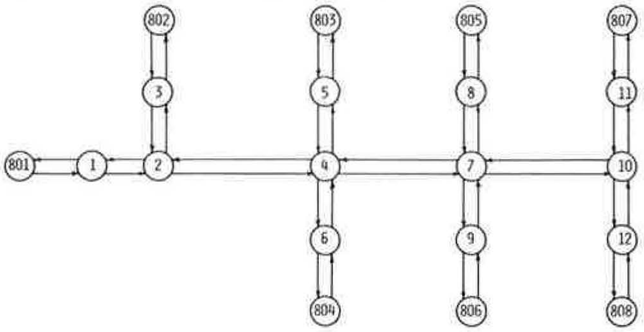
Figure 6. Prices Fork Road network.



average intersection discharge rate. For a base saturation headway of 2.2 s, and by using the adjustment factor suggested by Dick (12), saturation headways of 1.9 and 2.5 s were used to simulate the effect of -4 and +4 percent gradients, respectively. These values were input to NETSIM for the major-street approaches; a 2.2-s saturation headway was assumed for the minor-street approaches. The average fuel-consumption values (gallons per vehicle) estimated by NETSIM are attributed to traffic interaction only, and the possible effect of grade per se on fuel-consumption rates is not taken into account. Components for uniform speed and speed-change cycles as functions of grade have yet to be developed in a form suitable for NETSIM.

To illustrate the impacts of fuel-consumption and headway-distribution models on an actual network, a second set of analyses was performed for the Prices Fork Road arterial in Blacksburg, Virginia. The Prices Fork Road system is a small, open network that consists of four signalized intersections. The analyses were performed by using volumes measured in the morning peak period and a cycle length of 70 s at all intersections. The cycle splits and offsets used were obtained from the TRANSYT computer program (13). Cross-street volumes ranged from 10 to 940 vehicles/h, and link volumes on Prices Fork Road ranged from 260 to 1290 vehicles/h. The system as a whole, then, could be described as a moderate-volume operation. A physical description of the Prices Fork Road system is shown in Figure 6, and the link-node diagram is shown in Figure 7.

Figure 7. NETSIM link-node diagram for Prices Fork Road.



For the isolated intersection, the analyses are logically broken down into the four sets of simulation runs described in Table 1. Several replicates were simulated for each run (a minimum of four), each of 900-s duration. Several trials were attempted in order to select an optimum link length for both the major and minor streets. The optimum length should be long enough to prevent traffic spillback on the intersection approaches but should not be too long to negate the speed-change-cycle effect on fuel-consumption values at low volumes.

For the Prices Fork Road network, four cases were simulated for 1 h each:

1. Uniform headway distribution and NETSIM fuel models,
2. Uniform headway distribution and the modified fuel model,
3. Shifted-negative-exponential headway distribution and the NETSIM fuel model, and
4. Shifted-negative-exponential headway distribution and the modified fuel model.

Table 1. Layout of four simulation runs for hypothetical isolated intersection.

Run Group	Run Number	Headway Distribution	Saturation Headway (s)	Grade (%)	Fuel Model	Main-Street Volume (vehicles/h)
1	1	U	2.2	0	NETSIM	600
	2	U				1200
	3	U				1800
	4	SNE			NETSIM	600
	5	SNE				800
	6	SNE				1200
2	7	U	2.2	0	Modified	600
	8	U				1200
	9	U				1800
	10	SNE			Modified	600
	11	SNE				1200
	12	SNE				1800
3	13	SNE	2.0	0	Modified	600
	14	SNE				1200
	15	SNE				1800
	16	SNE				600
	17	SNE	2.4			1200
	18	SNE				1800
4	19	SNE	1.9[a]	4	Modified	600
	20	SNE	2.5[b]			1200
	21	SNE	2.2[c]			1800

Note: U = uniform; SNE = shifted negative exponential.

[a] Downgrade. [b] Upgrade. [c] Cross street.

Figure 8. Effect of fuel model: uniform distribution.

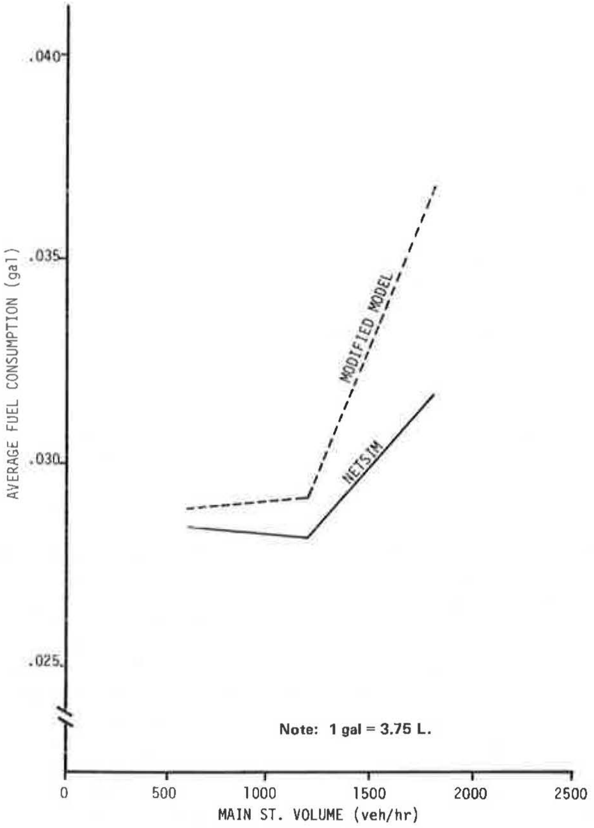
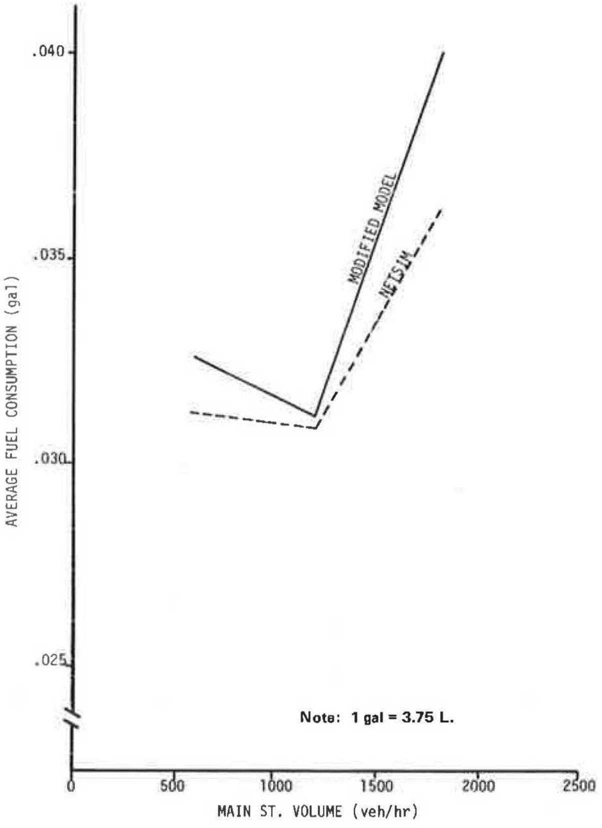


Figure 9. Effect of fuel model: shifted negative exponential distribution.



RESULTS

Isolated Intersections

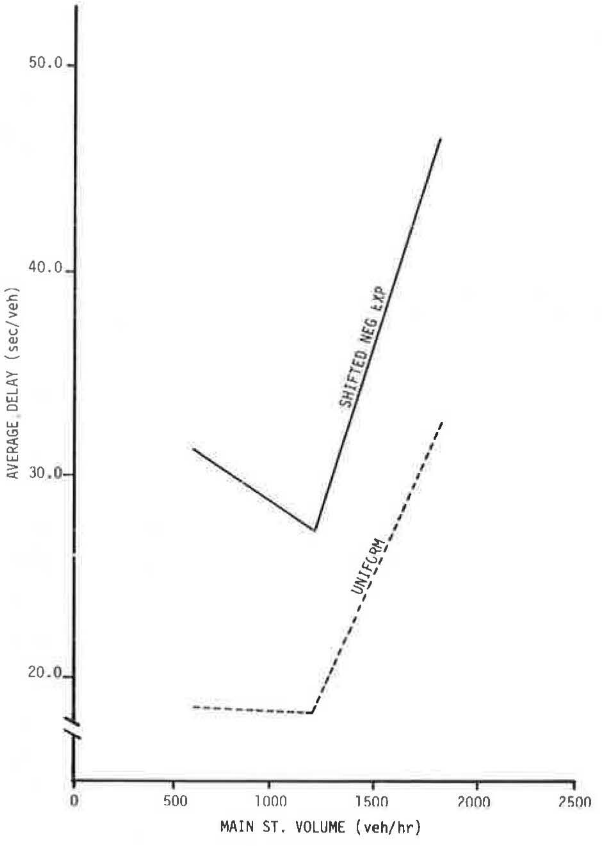
Fuel Models

By using the uniform headway distribution, it was found that the modified fuel model produced significantly higher fuel-consumption values at the 95 percent level than the NETSIM model. The difference between the two models, shown in Figure 8, increases with increasing main-street volume (or degree of saturation). A similar comparison in which the shifted-negative-exponential headway distribution was used indicated that there was no significant difference in the two fuel models (see Figure 9), although the modified fuel model gave consistently higher consumption values.

Headway Models

The average delay values for the shifted-negative-exponential headway distribution were found to be significantly higher than those of the uniform headway model (see Figure 10). For the range of main street volumes considered, the shifted-negative-exponential distribution produced values that were, on the average, 52 percent higher than those of the uniform distribution. This result suggests using the shifted-negative-exponential headway distribution instead of the uniform distribution when using NETSIM to simulate traffic through an isolated intersection. This is suggested because a "bunching" of vehicles can be represented through the use of the shifted-negative-exponential headway distribution, whereas the uniform headway distribution can-

Figure 10. Effect of headway model on delay.



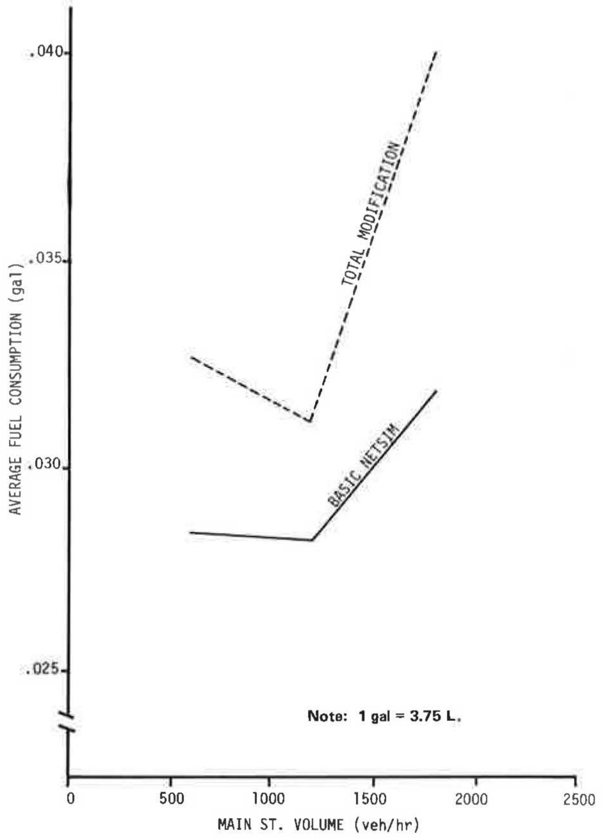


Figure 11. Overall comparison of fuel-consumption values.

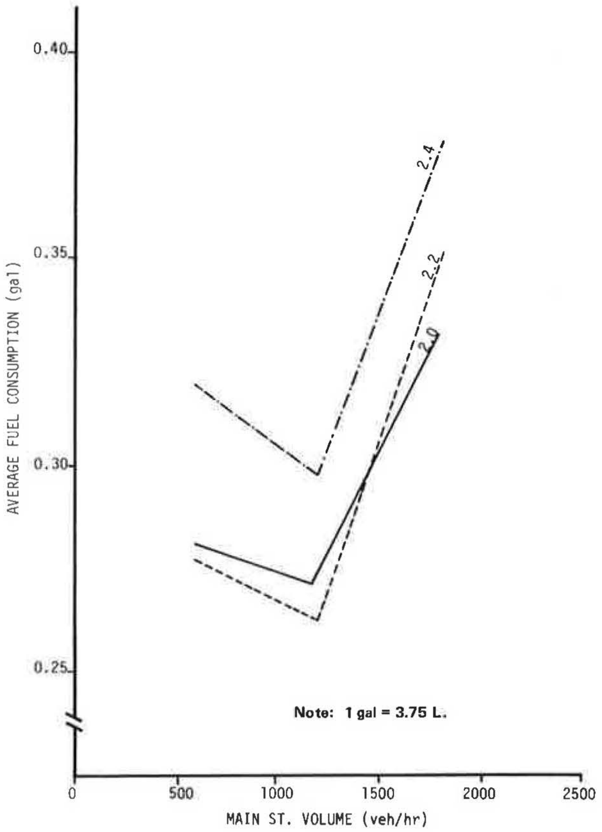


Figure 12. Effect of saturation headway on fuel consumption.

not reproduce this real-world traffic pattern.

In addition, fuel-consumption values were also found to be significantly different between the two headway distributions.

Overall Comparison

Figure 11 shows a comparison between the fuel-consumption values of the basic NETSIM model and a program modified to incorporate both the modified fuel model and the shifted-negative-exponential headway distribution. The results, which are significant, indicate that fuel-consumption values from the "totally modified" model average 17.4 percent higher than those of the basic NETSIM program. The delay differences would be the same as those shown in Figure 10.

Saturation Headway

The effects of saturation headway on fuel consumption and delay are shown in Figures 12 and 13, respectively. Increasing saturation headway from 2.0 to 2.2 s has no significant effect on either delay or fuel consumption. However, an increase in saturation headway from 2.2 to 2.4 s produces a significant effect on both delay and fuel consumption only for major-street volumes of 600 and 1200 vehicles/h.

Gradient Effects

The effects of grade on delay and fuel consumption on the main street were estimated by using changes in saturation-headway values (again, it should be noted that these changes do not include all of the effects of grade). As Figures 14 and 15 show, the

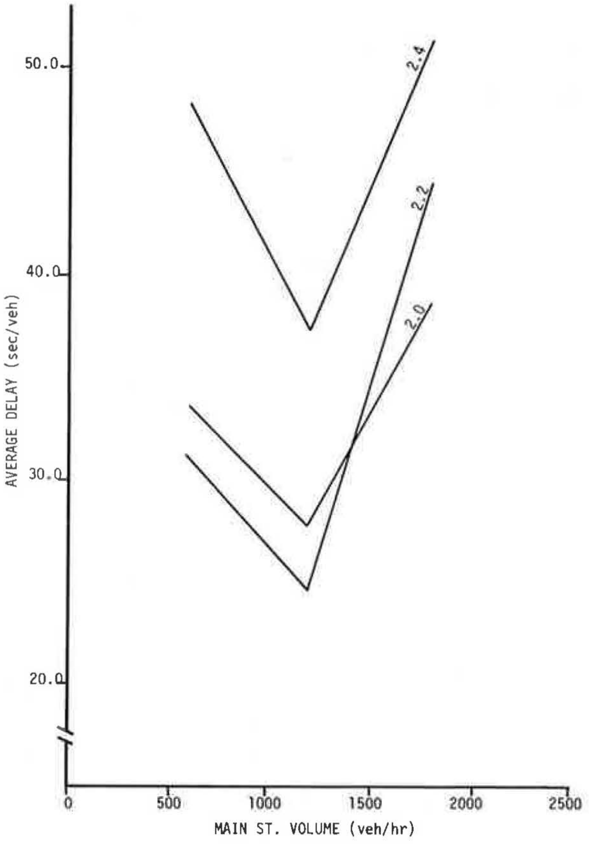


Figure 13. Effect of saturation headway on delay.

Figure 14. Effect of grade on fuel consumption.

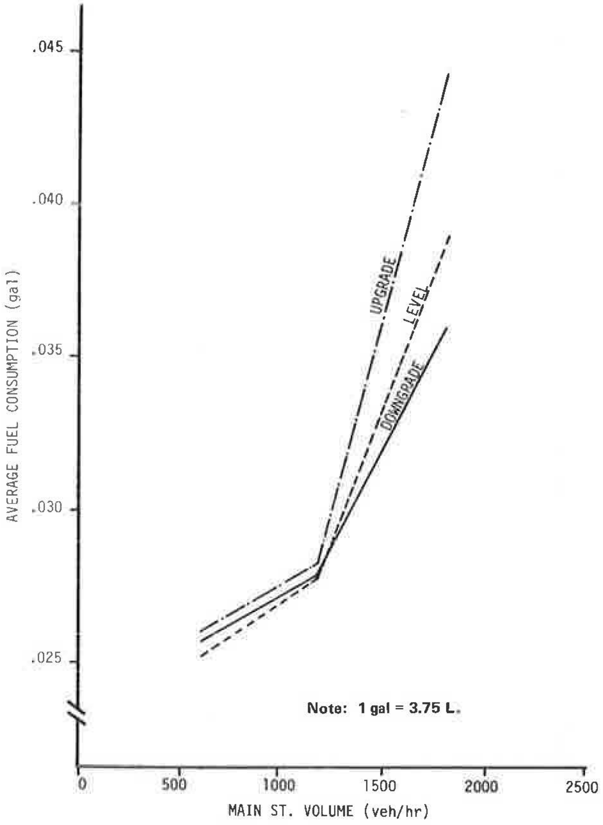
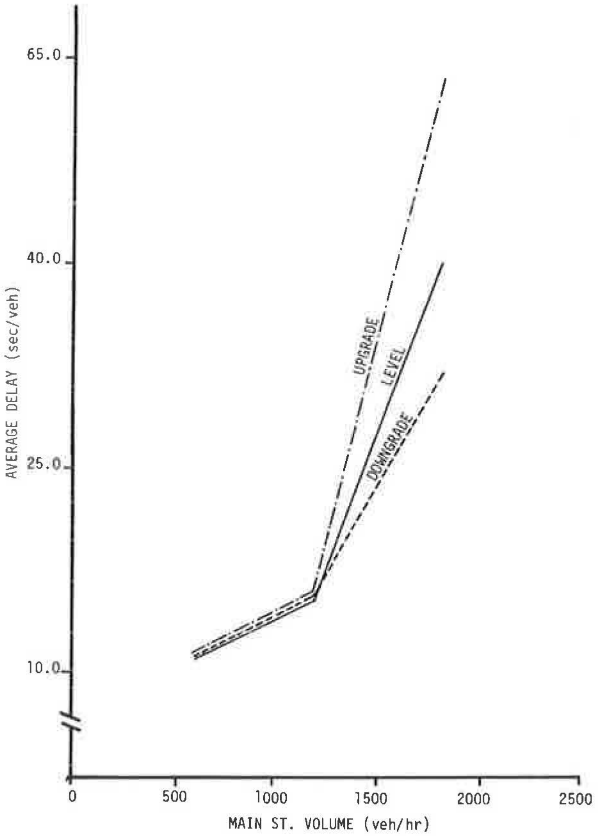


Figure 15. Effect of grade on delay.



results for both fuel consumption and delay showed no difference between zero and +4 or -4 percent grades at major-street volumes of 600 and 1200 vehicles/h. However, it was found that both delay and fuel-consumption values for the +4 and -4 percent grades were significantly different from those for zero percent grade for a major-street approach volume of 1800 vehicles/h. It appears that incorporating the effect of grade through changes in saturation headway can be useful at high volumes.

Prices Fork Road Network

The results of the Prices Fork Road analyses are summarized below (1 gal = 3.75 L):

Headway Model	Fuel Consumption (gal) NETSIM	Modified Model	Delay (s/vehicle)
Uniform	155	169	53.4
Shifted negative exponential	192	199	92.5

The shifted-negative-exponential headway model shows an average delay per vehicle that is 73 percent greater than that for the uniform-headway-distribution model. Similarly, a change in headway models from the uniform to the shifted negative exponential causes increases in fuel-consumption estimates of 24 percent for the NETSIM fuel model and 18 percent for the modified model. A change from the basic NETSIM program to one that uses both the modified fuel model and the shifted-negative-exponential headway distribution results in a 28 percent increase in the estimate of fuel consumption.

CONCLUSIONS

The modified-fuel-consumption model developed in this study produced fuel-consumption values higher than those of the NETSIM model for both the uniform and shifted-negative-exponential headway distributions. NETSIM has proved to be an efficient tool in simulating traffic through large networks, especially at high volumes. The results of the headway-distribution model runs for the isolated intersection and the Prices Fork Road network suggest that the shifted-negative-exponential distribution should be used instead of the uniform distribution for simulating traffic at isolated intersections and small, open networks, especially those with low to moderate traffic volumes.

NETSIM results proved to be sensitive to saturation headways greater than 2.2 s. Reducing the saturation headway to less than 2.2 s does not significantly affect the results from the simulation model. Except for high-volume conditions, both delay and fuel consumption were found to be insensitive to the effect of grade on saturation flow rate.

The results of this research do not answer all significant questions concerning the universality of the conclusions drawn from the NETSIM simulations. For example, the results presented show that there is a significant difference between fuel models, although no statement is made as to which of the two is best. The fact is that both models are based on old vehicles and an entirely new model needs to be developed based on field tests with newer vehicles. Modeling of field-based truck fuel consumption should also be included in NETSIM, and sensitivity analyses should be performed with respect to traffic mix. The present inability of the program to consider the effect of grade on fuel consumption is of concern. Such a capability needs to be developed and sensitivities analyzed. Other headway distributions such as the Erlang, Lognormal, Pearson, and Composite models should be investigated. Only when there is a thorough understanding of the significant variables and their impact on fuel consumption can any reliable conclusions be drawn concerning signal timing for the purpose of minimizing fuel consumption. It is felt that, of the available computer programs, NETSIM offers the greatest potential for determining these requirements.

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Abridgment

Traffic Data Acquisition from Small-Format Photography

L.J. MOUNTAIN AND J.B. GARNER

A simple and economical method for collecting traffic data at complex urban intersections is described. The technique, developed at the University of Leeds, involves the collection of data in digital form by use of small-format photography taken from a hovering helicopter. The data are obtained in this form by means of a coordinate reader and processed by means of a computer that, using a two-dimensional coordinate transformation system, transforms the data to ground data and outputs information on a range of traffic-flow parameters. These parameters include approach volumes, the origins and destinations of all vehicles followed through the intersection, and the mean journey time and speed for each route. The potential of 16- and 35-mm photography to provide suitable photographic coverage is evaluated. The accuracy of the coordinate transformation systems is determined, and a computer-based coordinate-matching technique is developed. Finally, the accuracy and costs of obtaining traffic data by using the technique are compared with those associated with more conventional ground-survey methods. It was found that, where comprehensive traffic data are required, the technique can provide a simple, accurate, and economical method of traffic data collection and could be a workable alternative to conventional ground-survey methods.

While conventional ground-survey methods seem incapable of keeping abreast of the expanding data needs of today's traffic engineers, photographic techniques appear to have the potential to do so, particularly when combined with modern coordinate reader and computer technologies (1). The major problem associated with photographic techniques has, in the past, always been the difficulties associated with extracting and analyzing the vast quantities of information available from photographs (2), a problem that is particularly acute at intersections because of the complex nature of traffic movements at such locations. The basic objective of the research described in this paper was to find a solution to this problem.

STUDY AREA

The site selected for study in this project was a complex double roundabout system near the center of Bradford in northern England. One portion of the system has five legs and the other has three, which gives a total of 36 possible routes through the study area. In order to include any queues on the approaches, it was decided that it would be necessary to include a minimum distance of 50 m on each approach to the roundabouts. Thus, the minimum area of coverage necessary was approximately 0.15x0.31 km.

DATA COLLECTION

To obtain comprehensive traffic data at such a location, it is essential that the photography used should be capable of providing continuous coverage of the entire intersection for a period of at least 1 h. Time-lapse photography is immediately suggested, but using any type of ground camera position would have restricted the field of view too much. A better vantage point could be obtained from the air,