# Operating Costs at Intersections Obtained From The Simulation of Traffic Flow

EARL R. RUITER, Traffic Planning Analyst, Chicago Area Transportation Study, Chicago, Illinois*, and
PAUL W. SHULDINER, Associate Professor of Civil Engineering, Northwestern University, Evanston, Illinois

A computer program has been written which simulates the traffic at an urban intersection, and determines both delays and fuel consumption of vehicles passing through the intersection. By placing typical unit costs on hours of time and gallons of fuel, operating costs are determined for each vehicle and then averaged for all vehicles traveling on each of the two streets. The variable inputs to the program include type of intersection control (two-way stop or semi-traffic-actuated signal), volume levels, turning percentages, critical lag at the stop sign or signal phasing and detector locations for the traffic signal, sampling time, and vehicle fuel consumption characteristics. The program is written for an IBM 704-709 computer and has an approximate real time to computer time ratio of four to one.

To illustrate the usefulness of the program in the economic analysis of intersections, the program was run at various combinations of main street and side street volumes under both traffic signal and stop sign control. The cost contours for each type of intersection control were compared to find areas where stop sign control resulted in the lowest operating costs, where traffic signal control was cheapest, and where the two types of control resulted in equal operating costs. The line of equal operating costs can be considered a warrant line separating traffic signal preferability from stop sign preferability.

•AS AN AID in the selection among alternative transportation improvements, highway and traffic engineers have made extensive use of a form of economic analysis which involves the evaluation of the anticipated effects of each alternative upon road-user costs. Direct vehicle operating costs constitute a major element in such analyses, and much effort has, therefore, gone into determining how these costs vary with speed, gradient, curvature, and pavement and vehicle type (1, 10, 15). The excess cost of stopping over that of traveling at various constant speeds has also been studied (1).

A gap in the knowledge exists, however, in the case of predicting operating costs at intersections. Besides the previous factors, it appears that operating costs vary with volume and type of control. Because these relationships are not known exactly, traffic engineers now resort to noneconomic methods of justifying expenditures at intersections. One such method is the use of warrants based on engineering judgment and on observations of intersection performance. Warrants have been developed for stop sign and traffic signal intersection control (11, 13). Another noneconomic method is the

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*Formerly, Graduate Student and Research Assistant, Civil Engineering Department, Northwestern University.

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use of sufficiency ratings which gave an indication of the priority and need of various improvements (14).

A method of accurately predicting operating costs at all intersections would make it possible to replace warrants based on judgment and observation of performance with warrants based on minimizing the total costs associated with the intersection. Also, individual projects proposed to improve a given intersection could be compared by means of the normal methods used in engineering economy.

The purpose of this paper is to report on a method of predicting operating costs at intersections using traffic simulation techniques. The use of the method is illustrated by the development of warrants based upon the minimization of operating costs.

## Prediction of Operating Costs at Intersections

In the past, intersection studies have concentrated on describing vehicle behavior such as average headways, delays and queue lengths, as well as the variations in these factors with changes in volume level. Time-lapse photography and various types of delay meters have been used to study vehicle operating characteristics in the field. More recently, analytical models have been developed using probability and queueing theory (12, 13) and Monte Carlo methods for the simulation of vehicle behavior (5, 9). Each of these techniques has its own inherent advantages and disadvantages. However, Monte Carlo simulation holds, perhaps, the greatest promise through its ability to deal with complex probabilistic situations for which no direct analytical method of solution is known.

For this reason, the simulation method was chosen as a basis for the development of a method for predicting operating costs at intersections. The model which was developed is a combination of two previously developed computer programs. The simulation program which was used is that developed by Lewis (8, 9). Fuel costs are obtained using the methods developed by Robbins (6, 7). The combined program predicts fuel and time costs, the two largest factors in operating costs. Among the factors which are not considered are oil, tire, maintenance and depreciation costs.

Lewis' program simulates the operation of the intersection of a four-lane and a two-lane street. The choice of traffic control is limited to either stop signs on the minor street or a semi-actuated traffic signal.

Robbins' program calculates the speed profile and fuel consumption of a representative vehicle traveling over a given highway alignment. The speed profile is limited by driver preferences and vehicle characteristics. Fuel consumption is determined by calculating piston speed and brake horsepower required per square inch of piston area for each time interval. A value of fuel per brake horsepower hour can then be read from a fuel map relating this quantity to piston speed and brake horsepower required per square inch of piston area.

## Description of the Modified Program

In order to obtain operating costs for vehicles passing through intersections, it was decided to modify the intersection simulation program written by Lewis so that it would calculate the fuel consumption of each vehicle as it moves through the intersection area. The method of calculating fuel consumption is essentially the same as that developed by Robbins (6). Total operating costs are obtained for each vehicle as it is released from the intersection by adding its accumulated fuel costs (fuel consumption multiplied by gasoline cost) to its time cost (total time spent by the vehicle in the system multiplied by the value of time). These total operating costs are then accumulated for all vehicles starting in a given lane and performing a given turning maneuver.

## Simplifying Assumptions

A number of the assumptions used to simplify the model are those employed by Lewis in formulating his simulation program:

1. Vehicles travel so as to minimize their delays.

2. Factors such as minimum spacing of vehicles, maximum speeds, acceleration and deceleration rates, and acceptable gaps are constants for all drivers and all vehicles.
3. Pedestrians have no effect on drivers.
4. The opportunity to pass is limited to straight through vehicles following turning vehicles.

Other simplifying assumptions were necessary in order to make the Lewis' and Robbins' programs compatible. These assumptions include the following:

1. All operating costs except fuel and time costs can be ignored.
2. The effects of vertical grades and curve resistances on fuel consumption at intersections can be ignored.
3. Vehicles are capable of performing according to their drivers' preference; they are not limited by the vehicles' capabilities as in Robbins' program.
4. All vehicles using an intersection can be represented by one vehicle type, with one set of vehicle characteristics.

### Resulting Program

The major addition to the Lewis program is the provision of a method of calculating fuel consumption for each vehicle during each time interval. By applying the simplifying assumptions to the Robbins' procedure, the following method for computing fuel costs was obtained:

1. Determine the acceleration rate, average speed, and distance traveled during the time interval, based on the maximum desired speed, and limited by spacing, acceleration, stopping, and turning restrictions.
2. Determine which gear the vehicle will be in.
3. Calculate the speed of the engine in revolutions per minute.
4. Calculate air, rolling, and acceleration resistances.
5. Calculate the brake horsepower required per square inch of piston area.
6. If the vehicle is idling at a stop or coasting, use a linear equation relating fuel consumption to engine speed to calculate the fuel consumption. If the vehicle is not idling or coasting go to step 7.
7. Calculate the rate (feet per minute) of piston travel.
8. Use the results of steps 5 and 7 to find from the fuel map the amount of fuel per brake horsepower hour which will be consumed.
9. Multiply the results of step 8 by the brake horsepower and the time increment to determine the amount of fuel which will be consumed during the current time interval.

Lewis' input routines were modified so that the vehicle data needed to calculate fuel consumption could be read in. Output routines were modified so that they would calculate and print out operating cost data in addition to the delay data given by the original program.

The modified program has a real time to computer time ratio of four to one, using an IBM 709 computer.

## USE OF THE PROGRAM

### Selection of the Input Data

Most of the input data were chosen to correspond to that used by either Lewis or Robbins in their individual programs. The fuel map and vehicle type (1960 Plymouth station wagon) were those used by Robbins. The intersection parameters were those used by Lewis. A summary of these data is given in Table 1.

Computer test runs were made to insure that the action of the vehicles had not been changed from the experience in the unmodified program. Fuel consumption rates were determined and checked for reasonableness. Also, the variability or ratio of standard deviation to means of the operating costs for individual vehicles was

TABLE 1

PARAMETERS AND INPUTS USED TO OBTAIN VOLUME WARRANTS

| | |
|---|---|
| Parameters: | |
| Maximum desired speed | 44 fps |
| Maximum acceleration rate: | |
| Normal conditions | 3 $\text{fps}^2$ |
| Starting from stop | 6 $\text{fps}^2$ |
| Maximum deceleration rate: | |
| Normal conditions | 6 $\text{fps}^2$ |
| Stopping at amber light | 12 $\text{fps}^2$ |
| Arrival distribution | Modified binomial |
| Minimum vehicle spacing | 22 ft |
| Inputs: | |
| Fuel map | Typical for gasoline engines |
| Vehicle | 1960 Plymouth station wagon |
| Gasoline price | $0.33/gal |
| Time cost | $1.50/hr |
| Transient time | 300 sec |
| Sample time | Variable |
| Distance of detectors from stop lines | 21 ft |
| Critical lags | 5.8 sec |
| Lane volumes | Variable |
| Traffic signal controller intervals: | |
| Main street | |
| Minimum green | 30 sec |
| Amber | 3 sec |
| Side street | |
| Initial green | 2 sec |
| Extension green | 4 sec |
| Maximum green | 30 sec |
| Amber | 3 sec |
| Directional distributions | 60%-40% |
| Lane distribution, 4-lane streets: | |
| Outside lane | 60% |
| Inside lane | 40% |
| Turns, % of total volume: | |
| Main street, both turns | 7 each |
| Side street, both turns | 14 each |

checked so that production run time could be chosen which would result in a uniform level of accuracy from one operating cost figure to another.

## Selection of Computer Running Times

As a first step in running the modified program, it was necessary to determine the duration of run required at each volume level to attain a preselected level of significance. An equation relating duration of run to volume was derived (see Appendix). The sample time for each run was determined by use of this equation for both main and side street volumes. The largest of the two durations prescribed was then selected. The resulting savings in machine time amounted to approximately 30 percent when compared with the commonly used constant sample time of one hour.

## Warrants for Intersection Control

One of the underlying purposes of the modified program is the developing and testing of intersection control warrants based on minimum average vehicle operating costs. Two types of intersection control (stop sign and semi-actuated signal) and a range of main street volumes (400 to 1,400 veh/hr) were tested at side street volume levels chosen so as to lie on both sides of the minimum delay warrant line developed by Lewis. Additional side street volume levels were tested in those instances where the initial pair of volumes did not define the preference boundary.

The results of these runs are given in Tables 2 and 3. Table 2 summarizes the values derived assuming traffic signal control; the results for the stop sign condition are given in Table 3. Figure 1 presents these data in terms of equal cost contours for both types of control for all levels of side street and main street volumes which were considered. The intersection of equivalent contour lines indicates combinations of side street and main street volumes for which vehicle operating costs are equal for both traffic signal and stop sign control. A warrant line may be drawn through these points representing the minimum vehicle operating cost boundary between these two types of traffic control. Such a curve is shown in Figure 2 (solid line) along with the minimum delay warrant line developed by Lewis.

For the most part, the equal cost contours indicate that average operating costs increase with both types of control as either side street or main street volumes increase. At high levels of side street volume, however, the apparently anomalous situation exists of average vehicle costs decreasing with increasing main street volumes. If it is recalled that we are dealing with average vehicle operating costs, the explanation becomes fairly obvious. At constant side street volumes (and constant side street costs), the average side and main street costs decrease as a result of the increased proportion of lower main street costs brought about by increasing the number of main street vehicles. These contours would begin to slope downward to the right as congestion on the main street increases the main street vehicle operating costs.

Since there is an added cost associated with installing a signal light at an intersection instead of a stop sign, the warrant line in Figure 2 is not strictly applicable. However, when the cost of a signal light is capitalized over its useful life and the cost per vehicle is determined, it will be very low.

## TABLE 2

## WARRANT PRODUCTION RUNS—TRAFFIC SIGNAL CONTROL

| Nominal Volumes (veh/hr) | | Actual Volumes (veh/hr) | | Avg. Operating Costs ($/veh) | | |
|---|---|---|---|---|---|---|
| MS[a] | SS[b] | MS[a] | SS[b] | MS[a] | SS[b] | Both[c] |
| 400 | 400 | 410 | 403 | 0.0139 | 0.0224 | 0.0181 |
| | 500 | 418 | 482 | 0.0135 | 0.0234 | 0.0188 |
| | 600 | 418 | 518 | 0.0140 | 0.0241 | 0.0196 |
| | 650 | 403 | 619 | 0.0158 | 0.0220 | 0.0195 |
| 600 | 150 | 624 | 160 | 0.0117 | 0.0234 | 0.0140 |
| | 200 | 622 | 206 | 0.0125 | 0.0244 | 0.0155 |
| | 250 | 624 | 216 | 0.0129 | 0.0212 | 0.0150 |
| | 350 | 657 | 342 | 0.0143 | 0.0219 | 0.0169 |
| | 400 | 630 | 414 | 0.0149 | 0.0229 | 0.0181 |
| 800 | 150 | 832 | 160 | 0.0126 | 0.0234 | 0.0143 |
| | 250 | 822 | 216 | 0.0132 | 0.0212 | 0.0149 |
| 1,000 | 75 | 1,068 | 80 | 0.0121 | 0.0222 | 0.0128 |
| | 175 | 1,062 | 158 | 0.0124 | 0.0214 | 0.0136 |
| 1,200 | 50 | 1,241 | 64 | 0.0122 | 0.0206 | 0.0126 |
| | 100 | 1,288 | 105 | 0.0129 | 0.0233 | 0.0137 |
| | 150 | 1,272 | 160 | 0.0134 | 0.0234 | 0.0145 |
| 1,400 | 25 | 1,428 | 21 | 0.0110 | 0.0194 | 0.0111 |
| | 75 | 1,494 | 80 | 0.0129 | 0.0221 | 0.0134 |

[a] MS = main street.
[b] SS = side street.
[c] Both = both main and side streets.

## TABLE 3

## WARRANT PRODUCTION RUNS—STOP SIGN CONTROL

| Nominal Volumes (veh/hr) | | Actual Volumes (veh/hr) | | Avg. Operating Costs ($/veh) | | |
|---|---|---|---|---|---|---|
| MS[a] | SS[b] | MS[a] | SS[b] | MS[a] | SS[b] | Both[c] |
| 400 | 400 | 389 | 363 | 0.0100 | 0.0214 | 0.0155 |
| | 500 | 385 | 508 | 0.0099 | 0.0247 | 0.0183 |
| | 600 | 385 | 580 | 0.0099 | 0.0254 | 0.0192 |
| | 650 | 385 | 608 | 0.0099 | 0.0257 | 0.0196 |
| 600 | 150 | 642 | 165 | 0.0101 | 0.0256 | 0.0132 |
| | 200 | 619 | 207 | 0.0101 | 0.0318 | 0.0155 |
| | 250 | 623 | 263 | 0.0101 | 0.0309 | 0.0163 |
| | 350 | 672 | 309 | 0.0101 | 0.0331 | 0.0174 |
| | 400 | 645 | 353 | 0.0101 | 0.0369 | 0.0196 |
| 800 | 150 | 877 | 165 | 0.0098 | 0.0293 | 0.0129 |
| | 250 | 834 | 254 | 0.0099 | 0.0430 | 0.0176 |
| 1,000 | 75 | 1,039 | 71 | 0.0100 | 0.0349 | 0.0116 |
| | 175 | 1,073 | 179 | 0.0100 | 0.0581 | 0.0169 |
| 1,200 | 50 | 1,235 | 48 | 0.0100 | 0.0428 | 0.0112 |
| | 100 | 1,221 | 99 | 0.0101 | 0.0520 | 0.0132 |
| | 150 | 1,246 | 170 | 0.0102 | 0.1791 | 0.0305 |
| 1,400 | 25 | 1,421 | 21 | 0.0102 | 0.0542 | 0.0108 |
| | 75 | 1,432 | 71 | 0.0102 | 0.1073 | 0.0148 |

[a] MS = main street.
[b] SS = side street.
[c] Both = both main and side streets.

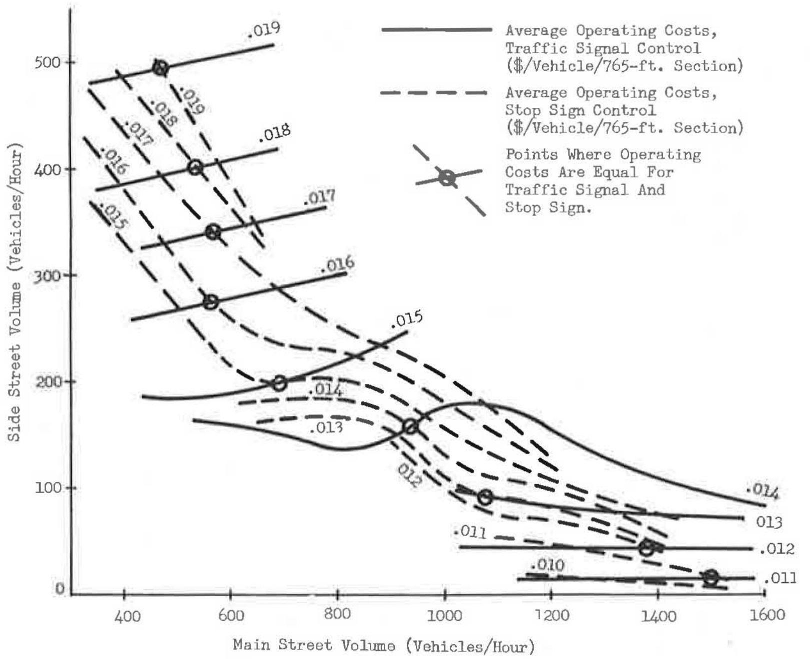

Figure 1. Contour map of vehicle operating costs at an intersection.

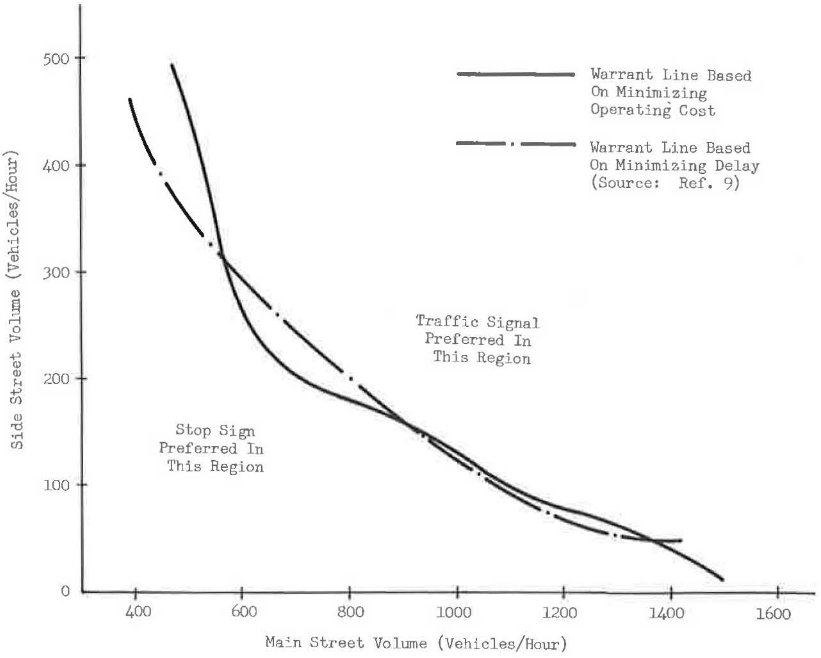

Figure 2. Comparison of warrant lines—minimum cost and minimum delay.

TABLE 4

VOLUME WARRANTS FOR PRETIMED SIGNALS[a]

| Number of Lanes | | Volumes | |
|---|---|---|---|
| MS | SS | MS | SS |
| (a) Warrant I—Minimum Volume | | | |
| 4 or more | 2 | 600 | 250 |
| 2 | 4 or more | 500 | 333 |
| (b) Warrant II—Interruption of Continuous Traffic | | | |
| 4 or more | 2 | 900 | 125 |
| 2 | 4 or more | 750 | 167 |

[a] Derived from Manual on Uniform Traffic Control Devices, pp. 185-186; pretimed signals are warranted whenever the intersection volumes exceed those given for 8 hr per day.

## Comparison with Other Warrants

Figure 2 shows graphically the difference between the minimum delay warrant developed by Lewis and the minimum operating cost warrant. The curves are nearly the same for main street volumes higher than 900 veh/hr. The entire operating cost curve, however, is more sharply "kinked" and therefore lies below Lewis' curve in the 550 to 900 main street volume range and above it for lower volumes.

The warrants based on operating costs can also be compared with those given in the Manual on Uniform Traffic Control Devices (11) for pretimed traffic signals (Table 4). The side street volume figures are given for both directions of approach, obtained from the Manual warrants by assuming a 60 to 40 percent directional distribution. If these warrants are interpreted strictly, the warrant line separating stop sign preference from signal light preference appears as a series of right-angled steps (Fig. 3). The lower corners of these steps are the points specified in Table 4, with changes of designation so that the main street is always the one with four traveled lanes and the side street the one with two traveled lanes. If the warrants are interpreted more loosely, the warrant lane can be obtained by drawing a smooth curve through the points given in Table 4. Such a curve is also shown in Figure 3.

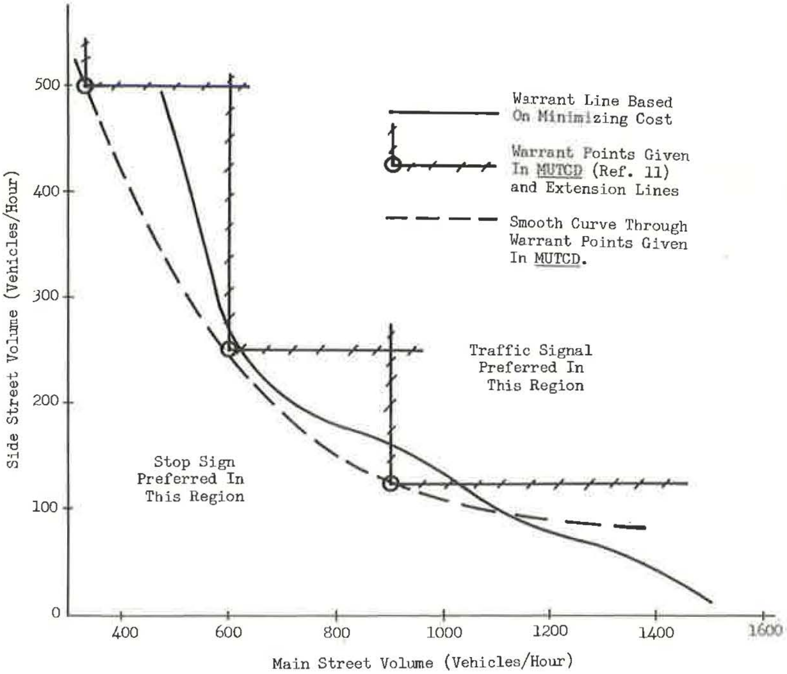

Figure 3. Comparison of warrant lines—minimum cost and Manual on Uniform Traffic Control Devices.

When discussing traffic-actuated signals the Manual states that they are warranted "at intersections where the volume of vehicular traffic is not great enough to warrant pretimed signals, . . . if other conditions indicate the need for traffic control signals and justify the cost of installation." (11, p. 200) This seems to indicate that if the Manual gave specific volume warrants for actuated signals, they would be lower than those given for pretimed signals.

Figure 3 indicates that the warrant for semi-actuated signals based on operating costs and the volume warrants for pretimed signals given in the Manual would result in the same choice of intersection control (stop vs signal) in most cases. However, if the Manual curves were shifted downward to any great extent to serve as actuated signal warrants, the result would be that at many volume combinations at which signals would be chosen they would result in higher operating cost than would stop signs.

A number of factors must be kept in mind before applying the warrant for intersection control based on operating costs. One of these factors is that the warrant is based on only one criterion of many possible criteria. Operating costs are minimized, but there is no recognition of such factors as pedestrian volumes, accident experience, and the need of progressive movement. Of course, the desire to minimize delays is taken into account by assigning a cost to a vehicle's time.

Another factor which must be recognized is that the warrant is based on a host of assumptions as to drivers' characteristics, traffic characteristics, and fuel consumption characteristics of a representative vehicle. Changes in any of these parameters will affect the warrant line obtained.

The warrant line based on minimizing total operating costs is presented, therefore, not as the answer to the problem of what type of control to install at a given intersection, but as an example of how the operating costs at intersections program can be used. Once satisfactory values are found for all the parameters involved, similar warrants could be developed which could be combined with warrants based on other criteria in a handbook such as the Manual on Uniform Traffic Control Devices.

## CONCLUSIONS

The addition of the calculation of operating costs to an intersection simulation model has provided a model which enables the engineer to analyze more accurately the operating costs associated with intersections. These data are especially useful when determining the type of intersection control which should be used at intersections on major highways, whether this "control" is a stop sign, traffic signal, or the elimination of the intersection by interchange.

The volume warrants based on minimizing operating costs provide an economic method of determining whether traffic signals or stop signs should be used at intersections. This economic method can easily be improved by adding other costs (accident, oil consumption, etc.) as they become available. The warrants developed here are in general agreement with the existing warrants given in the Manual on Uniform Traffic Control Devices.

## ACKNOWLEDGMENTS

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The authors wish to acknowledge also the assistance of Professor Russell M. Lewis who consented to the use and modification of his intersection simulation program. The Civil Engineering Systems Laboratory at the Massachusetts Institute of Technology was helpful in providing details on the vehicle operating cost method developed by David H. Robbins.

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# *Appendix*

## Selection of Run Times

The method used to determine the sample time necessary to achieve a desired degree of accuracy follows:

Since we are concerned with comparing sample means with population means when the standard deviation of the population ($\sigma$) is unknown, the two-tailed t test is applicable (3).

$$t_{(\frac{1}{2}\alpha)\ (N-1)} = \frac{\bar{x} - M}{s/\sqrt{N}} \tag{1}$$

in which

$t$ = statistic used to test for equality of population mean and sample mean when $\sigma$ is unknown;
$\alpha$ = the probability of rejecting a true hypothesis;
$N-1$ = degrees of freedom of t distribution;
$x$ = sample mean;
$M$ = population mean;
$s$ = sample standard deviation; and
$N$ = number of observations in the sample.

We wish to keep the difference in means ($\bar{x}$ - M) less than or equal to a given fraction (p) of $\bar{x}$. Therefore, let

$$d = (\bar{x} - M) = p\,\bar{x} \tag{2}$$

Substituting Eq. 2 into Eq. 1 and solving for N,

$$N = \left(\frac{t_{(\frac{1}{2}\alpha)\ (N-1)}\ s}{d}\right)^2 \tag{3}$$

N is related to the volume level Q (veh/hr) and the elapsed time T (seconds) by

$$N = QT/3,600 \tag{4}$$

The variability of the sample data (V) may be defined in the following manner:

$$V = \frac{s}{\bar{x}} = \frac{ps}{d} \tag{5}$$

Substituting Eqs. 4 and 5 into Eq. 3 and solving for T, we obtain the final relationship for the sample time required to give a desired level of accuracy:

$$T = \frac{3,600}{Q}\left(\frac{t_{(\frac{1}{2}\alpha)\ (N-1)}\ V}{p}\right)^2 \tag{6}$$

## TABLE 5

## DETERMINATION OF SAMPLE TIME REQUIRED

| Control | Street[a] | Volume Level (veh/hr) | Avg. Total Cost ($/veh) | Std. Dev. of Total Cost ($/veh) | Variability | Eq. for Sample Time Required[b] |
|---|---|---|---|---|---|---|
| Semi-actuated traffic signal | MS | 252 | 0.0151 | 0.00687 | 0.455 | $T = 192,000/Q$ |
| | SS | 365 | 0.0203 | 0.00762 | 0.375 | $T = 130,000/Q$ |
| Stop sign | MS | 252 | 0.00991 | 0.00639 | 0.648 | $T = 388,000/Q$ |
| | SS | 367 | 0.01961 | 0.00976 | 0.497 | $T = 229,000/Q$[c] |

[a] MS = main street; SS = side street.
[b] $T$ = sample time (sec); $Q$ = traffic volume (veh/hr).
[c] Later modified to $T = 412,000/Q$, as described in the text.

In order to use Eq. 6 to determine the sample time required at a given volume level, values must be specified for $\alpha$, p, and V. An $\alpha$ value of 0.05 was chosen so that the results would be significant at the 95 percent level. The corresponding value of t depends on $N - 1$, the degrees of freedom, and N is unknown. However, t varies only slightly from a value of 2.0 for all values of N between 20 and infinity when $\alpha = 0.05$. Since it seemed likely that more than 20 vehicles would have to be sampled, t was assumed to have a constant value of 2.0.

A value of p, the allowable fraction of deviation in $\bar{x}$, of 0.125 was chosen since this is approximately the accuracy of the operating cost calculation method (6).

An analysis of the test runs indicated that the variability of the total operating costs depends both on the type of signal control and on which street is being considered. The results of this analysis are given in Table 5. Also given are the resulting equations for T obtained by substituting (into Eq. 6) the previous values given in Table 5.

If the equations for T given in Table 5 are accepted, the implicit assumption is made that the variability found at the volume levels used in the test runs would remain constant, regardless of volume level. This assumption was checked by making a second set of test runs, with volumes of 1,400 and 25 on the main street and side street, respectively. The variabilities for these volume levels were all lower than those given in Table 5, except for the stop sign side street case, where the new variability was 0.667, higher than the 0.497 given in Table 5. The equation for the sample time required for this case was therefore revised to $T = 412,000/Q$. Although the equation for T in each case could be further modified by making V a function of the volume level Q, this was not done because only limited information was available on the variation of V with Q. Since the two sets of test runs indicated that V tended to be a maximum at the intermediate volume levels, it was decided to use the maximum V's found in these tests and assume them to be constant for all values of the volume level. The net effect is to provide a factor of safety for high and low volumes to overcome the ignorance of the true value of V at these volumes.

## *Discussion*

RUSSELL M. LEWIS, Associate Professor of Civil Engineering, Rensselaer Polytechnic Institute—The authors have cleverly combined the work of D. H. Robbins on predicting operating costs of vehicles and the efforts of this writer in the development of a simulation model of a traffic intersection. They developed curves for direct operating costs based on the costs of fuel consumption and time. As an example of the use of these data, minimum volume warrants were presented for an actuated traffic signal.

A word of caution should be given in regard to the direct use of the operating cost data as given in Figure 1. The validation of simulation models, such as the one used, is a most difficult if not impossible task. To minimize the effects of inaccuracies in the formulation of the model, however, the procedure of model comparison may be used. Insofar as possible, identical models were used to represent the studied intersection as operated under the two types of traffic control—the two-way stop sign and the semitraffic-actuated signal. Any distortions present in the models are thus reflected in a similar manner in the results obtained from each model. The differences in operating cost, therefore, are more reliable than the absolute values of operating cost as obtained for either type of control. The use of model comparison also permits the elimination as direct considerations of such cost producing variables as pedestrian movements, parking interference, and local intersection characteristics.

One of the several advantages of the simulation method is that all variables may be precisely controlled. Traffic is generated by a Monte Carlo process using a probability distribution function and a pseudorandom-number series that can be reset at the beginning of each run. Since only the central tendency is specified, the traffic volume that actually occurs during a run will vary somewhat with different lengths of the run. By using the same length runs for the two different control types, identical traffic volumes occur. (Actually slight variations in traffic volume may occur due to differences in the pattern of releasing vehicles from the system at the beginning and end of runs under the two types of traffic control; such variations are very small for runs that simulate one hour of real traffic.) Furthermore, not only are the traffic volumes the same, but the exact pattern of vehicle arrivals is duplicated. The simulation model employed in this study contained a separate traffic generation and random number routine for each street, enabling the volume level to be varied on one street while retaining the identical traffic on the other street.

The variability of the results obtained from the simulation model is a function of both traffic volume and control type. As volume levels increase on either street, the variability decreases; also the variability is less for signal control than for stop sign control. The use of a constant run time for each set of parameters, therefore, may appear wasteful of machine time. The authors developed a procedure which related the duration of a run to the two street volumes and the type of control. Unfortunately, the employment of variable run times mitigates a most important advantage of the simulation method.

The use of a constant run time would have assured that comparisons in operating cost could be performed independently of any differences in the pattern of traffic that occurred during the periods sampled. In addition, constant run times yield traffic volumes that may be held constant on one street and varied in reproducible increments on the other street. This control over traffic volumes greatly assists in the analysis of the simulation data.

An analysis of the direct operating costs (which include time costs) and the published delay data (9) was performed by the writer. The cost of time represented a nearly constant amount of 70 percent of the cost of operation. Furthermore, the remaining operating costs (that due to fuel consumption alone) exhibited a wide amount of scatter. Therefore, it is indicated that not only is travel time the foremost factor, but also that it is more difficult to draw conclusions from operating cost when time is excluded. The value of time used by the authors was $1.50/veh hr. If a persons per vehicle ratio of 1.8 was assumed, this figure corresponds to $0.83 per person hour. Although it is most difficult to establish a monetary value of time, it is obvious that any increase in the value of time would further decrease the significance of fuel consumption as a factor of operating cost.

It is felt that the apparent differences between the two warrant lines shown in Figure 2 have been over emphasized by the authors. If a smooth curve were used for the warrant based on minimizing operating cost, it would be almost identical to the curve based on minimizing delay originally developed by the writer. The discrepancies as shown in Figure 2 may be largely due to the sampling procedures used, rather than to any basic divergence in warrant principles.

The operating cost information presented by the authors is of great interest and should prove useful in economic studies. For the purpose of developing warrants for intersection control they aptly point out that many other factors (such as accident potential, pedestrian movement, and control at adjacent intersections) must be considered. Delay is recommended as generally preferable to operating cost as the basis for intersection control volume warrants for the following reasons:

1. Delay represents the major portion of operating cost, and the inclusion of other direct operating costs does not materially affect the conclusions that would be drawn from delay alone.
2. Delay is the more readily measured quantity.
3. Delay is the most identifiable factor by the motorist and is dominant in his determination of acceptable intersection control techniques.

EARL R. RUITER and PAUL W. SHULDINER, Closure.—The authors wish to express their appreciation to Professor Lewis for his continued interest in the work using his simulation model. The points brought out in the discussion are conducive to a better understanding of the paper and of the problems involved in simulation in general and in the simulation of operating costs in particular.

Professor Lewis advocates the use of constant run times so that the problem of different patterns of traffic at constant nominal volumes does not arise. However, this problem does arise in reality. The authors feel that the statistical analysis provides a satisfactory method of dealing with the problem, whereas the use of constant run times ignores the problem. If the problem is ignored, the model is removed one more step than is necessary from the reality of random traffic.