same manner as a traditional, actuated controller.

The simulation model is based on a four-legged intersection of two one-way streets. The green times, cycle lengths, and other inputs to the pretimed emulator were calculated by using Webster's method.

The validation proceeded according to the following strategy. First, the simulation model was tested against Webster's pretimed delay model by using a pretimed signal emulator. Because Webster's delay model has gained widespread use and acceptance, comparison of the simulation with Webster's model should provide sufficient evidence of the validity of the simulation model. The actuated signal delay model was then tested against the validated simulation model under various conditions.

Delays at a pretimed signal were calculated for a range of total intersection volumes from 800 to 1600 vehicles/h (the intersection becomes oversaturated after this point) and equal volumes in both directions. Simulation was performed for the same volume ranges; the results are plotted in Figure 4. Figure 4 shows that under the entire range of volumes the delays obtained by simulation are very close to the delays obtained by the delay model. The simulation model was also tested against Webster's model for unequal volumes in two directions, and the results are shown in Figure 5. Again, the results demonstrate trends that are similar to the case of equal volumes in the two directions. Based on these two comparisons, we concluded that the simulation model is successful in reproducing the delay estimates provided by Webster's pretimed model and is, therefore, a useful tool for validating the modified version for traffic-actuated operation.

In validating the modified version, the model was first tested with equal volumes in both directions. The results are plotted in Figure 6. Figure 6 shows that the model results are very close to the simulation results. The model tends to underestimate the delay slightly under low volumes and to overestimate slightly under heavy volumes. The average difference, however, lies within a 10 to 15 percent range and is reduced to zero when the total intersection volume is approximately 1350 vehicles/h and the v/c ratio is 0.75.

Another series of simulation runs was performed to test the model for different volumes in two directions. Figure 7 illustrates the results of these runs for various volume levels. For each curve, vehicles per hour in one direction is shown. Vehicles per hour in the other direction ranged from 200 to 1200.

Similar trends between simulated and computed delays can be distinguished in the three sets of curves. The computed delays are lower than simulated delays at low to moderate volumes (v/c ratios from 0.44 to 0.74) by an average difference of approximately 10 percent and become equal when the total intersection volume is equal to 1350 vehicles/h and v/c ratio is 0.75. After this point, the computed delays become slightly higher than the simulated delays. The average difference is 1 percent for the 400-vehicles/h curves and 8 percent for the 600-vehicles/h curve.

SUMMARY AND CONCLUSIONS

In this paper a macroscopic model for estimating delays at vehicle-actuated signals was proposed. The model was tested by simulation and has given satisfactory results for a wide range of applications. The model is a simple, yet adequate, model that requires little computational effort even for a complex, multiphase signal operation. Based on the same principles as the most widely accepted model for estimating delay at pretimed signals, this macroscopic model is offered as a useful tool for a quantitative comparison of the two basic types of signal control.

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Abridgment

Cost-Effectiveness of RUNCOST Evaluation Procedure

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Currently there is emphasis on low-capital programs of transportation-system management (TSM). Regulations issued in 1975 by the Urban Mass Transportation Administration and the Federal Highway Administration require each urbanized area to develop a plan containing a TSM element and a transportation improvement program (TIP). The programs are designed to meet the short-range needs of urban areas through the efficient use of existing facilities. The goal is to reduce traffic congestion and to facilitate the flow of traffic. According to the regulations (1), one of the major categories of TSM action concerns the "efficient use of existing road space

through traffic operations improvements to manage and control the flow of motor vehicles." Better signalization and the progressive timing of traffic signals are examples of such TSM action and are the general focus of this paper.

Methodology of before-and-after evaluation of signal improvements is not standardized. The list of candidate measures of effectiveness is long (2), and only a fraction of the measures is included in the typical evaluation. Once the measures of effectiveness (MOE) are selected for a project, a wide range of choice remains in scope and depth of field data collection and office analysis. One available option is the use of the computer program RUNCOST to quantify before-and-after values of vehicle-operating cost, fuel consumption, and pollutant emission. The value of these MOE must be compared with the added expense of using RUNCOST.

The objective of this paper is to indicate the cost and effectiveness of using the RUNCOST procedure as a component of the evaluation methodology for traffic-signal systems.

The availability of the computer program RUNCOST was reported in 1972 (3). RUNCOST was written by the Federal Highway Administration (FHWA) in 1970 to eliminate the tedious process of manually entering the Winfrey tables of vehicle operating cost (4). The Winfrey tables give the cost per vehicle-mile to operate an automobile and four types of trucks at uniform speeds ranging from 0 to 80 mph. The Winfrey tables also provide the additional costs of accelerating or decelerating these vehicles through speed-change cycles. Operating costs include the expense of fuel, tires, engine, oil, maintenance, and depreciation.

The floating automobile must be equipped with a tachograph for the Winfrey tables to be used to full advantage. The tachograph charts are curves of speed versus time. The curves for selected floating-automobile runs are reduced in the office to series of coordinates of speed and time that are punched onto computer cards. The principal RUNCOST output for each run is the Winfrey cost (in cents) to operate each of the five types of vehicles according to speeds and speed changes recorded on the tachograph chart.

In addition to the Winfrey tables, the RUNCOST program also computes the dollar value of time of the run for each of the five vehicle types based on dollar values of time specified by the user. The program uses only the total time of the run and not the tachograph curve of speeds versus time. (Therefore time costs can be obtained from floating-automobile studies employing only stopwatches and manual calculations. Time costs are reported by RUNCOST as a useful by-product but are not the justification for using a tachograph and the RUNCOST program.)

The first application of RUNCOST to the evaluation of a signal system was reported by Chapman and Clark (5) for the Charleston, South Carolina, hybrid traffic control system (HTCS). The HTCS is a 90-intersection, grid signal system with a control center that unites analog and digital computers. Raynor (6) reported the characteristics of the system in 1970. The Chapman and Clark RUNCOST evaluation indicated annual network savings of $631 000 due to reduced operating costs. These savings amortized the $550 000 cost of the HTCS in less than 1 year. (If the annual network savings of $4 676 000 due to reduced time costs had been considered as well, the amortization period would have been found to be approximately 1 month.)

By comparison, an earlier evaluation by Chapman and Raynor (7) that did not use RUNCOST found that the amortization period lasted approximately 3 years. That manual evaluation considered only the reduction in stops and determined through macroscopic analysis the savings in vehicle-operating costs and also stopped-delay-time costs that were due to the reduction in stops.

The RUNCOST analysis was much more microscopic and comprehensive in its treatment of speed changes. Chapman and Clark concluded that the reduction in amortization period from 3 years by manual analysis to less than 1 year by RUNCOST is significant and that "the refinement provided by the RUNCOST program is justified in spite of extra effort and cost" (5).

In 1974 the RUNCOST program was expanded to include printout of fuel consumption and pollutant emission. The fuel consumption calculation is based on the Winfrey tables (4). The calculation permits the user to apply an adjustment factor to each of the five types of vehicles to account for changes in fuel consumption rates. The pollutant emissions are calculated separately for nitrogen oxides, hydrocarbons, and carbon monoxide for each of the five types of vehicles and are based on previous work by Curry and Anderson (8, p. 103, Table B-6). The emissions loaded into the program are for the 1968-1969 base vehicle. The user is permitted to apply a single emission adjustment factor to all types of emissions to account for changes since 1968-1969. Curry and Anderson (8) give some guidance in this regard. The program considers emissions at uniform speeds and for stops, but not emissions due to speed changes other than stops. A sample output of the expanded RUNCOST program is included as an appendix.

APPLICATION OF RUNCOST TO NORTHSIDE DRIVE

During 1973 to 1975 the city of Atlanta replaced 21 old, noninterconnected, volume-density controllers along an 11.65-km (4.5-mile) length of Northside Drive with new, actuated controllers that are interconnected and supervised by a digital computer at City Hall.

In 1975 the expanded RUNCOST program was applied to the evaluation of that signal-system improvement. The MOE for the evaluation included the following:

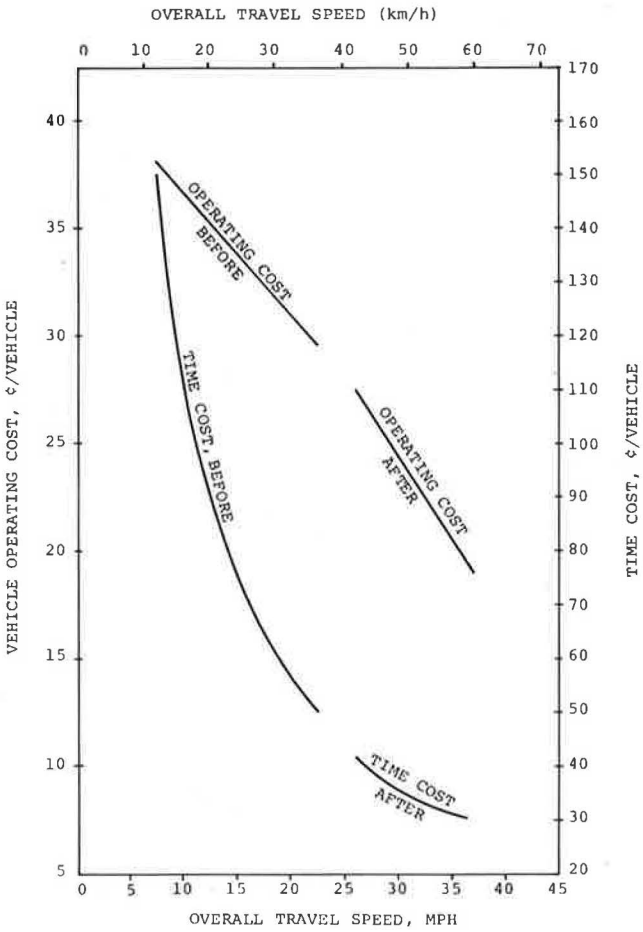
1. Level of service, A to F;
2. Stop probability, percent;
3. Average overall travel speed, kilometers per hour;
4. Vehicle operating cost, dollars;
5. Time cost, dollars;
6. Fuel consumption, liters;
7. Pollutant emission, kilograms; and
8. Volume, vehicles per day.

The results of the evaluation are reported in other studies (9, 10). A summary is given below.

Procedures and Costs

RUNCOST requires that the floating automobile be equipped with a tachograph. Montroll and Potts (11) and Parsonson (3) have reported the use of an instrument that has a 24-min by 7-revolution clock and a speed range of 0 to 129 km/h (0 to 80 mph). This instrument is a standard truck tachograph that has been modified slightly to give the expanded time scale required for traffic studies. The brake-signaler device is connected to a dash-mounted pushbutton for use as an event recorder. The instrument costs only a few hundred dollars, is quite reliable, and can be installed, serviced, and calibrated by most speedometer shops. Although the tachograph can be used for runs on short arterials without any peripheral equipment, usually including an inexpensive, dash-mounted, digital clock that reads

Figure 1. Operating cost and time cost versus speed during peak periods for zone 1.



seconds is desirable; including a portable tape recorder is also desirable. Both of these units operate from a dc-to-ac converter connected to the vehicle's battery. The cost of the equipment, installed, totals approximately $500. The driver can easily operate the equipment under all traffic conditions; an observer is never needed.

The office procedures begin with the labeling of all event marks on the tachographs. These event marks are the signalized intersections and, for short arterials, can be labeled directly. For longer runs the tape recording can be played back to eliminate the possibility of error in event-mark identification. At this point the stops are recorded on office forms. Then the average speed of each run is calculated manually by using travel times obtained either from the tachograph or from the tape recorder.

Only a few floating-automobile runs are selected for RUNCOST computer analysis. These runs should cover the range in observed speeds and the variation in vehicle-type distribution at different times of day. In the simplest case the vehicle population in a control section is observed to have approximately a constant distribution among the five types throughout the day. Then the only variation is in speed, and three runs in each direction of travel can be selected to cover the range encountered. Therefore the RUNCOST computer analysis would involve only six floating-automobile runs for the before condition and six for the after, for a total of 12 runs.

Figure 1 includes a relationship between vehicle-operating cost and overall travel speed. The data points that determined this relationship show some scatter from run to run to be about the best line. In view of this scatter, the recommendation for three runs in each direction might seem inadequate. However, Atlanta experience to date with four arterial sections indicates that the best line does not vary significantly by direction nor does the best line vary much from arterial to arterial (when plotted as operating cost per vehicle-kilometer of travel). The suggested total of 12 points is usually adequate to determine the relationship. As data accumulate from several projects, the need for additional RUNCOST analyses decreases.

Because a one-way, floating-automobile run in a single-control section is typically no more than 10 min in duration, the 12 runs represent 2 h of field data.

The coding of a run is the translation of the tachograph curve into an equivalent series of coordinates of speed and time. To code 1 h of field data, 2 to 3 h of clerical time are required. An additional ½ to 1 h is required to punch these cards and the associated control cards. Therefore the 2 h of field data from a single, simple-control section will require a maximum of 1 person-d for coding and punching.

By comparison, the Northside Drive evaluation was complicated by the fact that the vehicle-type distribution varied substantially between the peak periods and the midday off-peak periods. Also, there were three control sections. In all, 68 floating-automobile runs were selected for RUNCOST analyses. They represented 10 h of field data. Coding and punching of the cards required 5 d of clerical or subprofessional time. Computer charges average approximately $1.00/h of field data analyzed.

Results of the Evaluation

The three control zones combined showed an improvement in overall travel speeds of over 14.5 km/h (9 mph), quite constant throughout the day. The probability of having to stop at a given intersection along Northside Drive was reduced to only one-third to one-fourth of its before levels.

Figure 1 proceeds from the RUNCOST printouts and effectively demonstrates the reduction in vehicle-operating cost and motorist-time cost that is produced by a signal improvement that increases vehicle speeds. The absence of overlap between the before and after curves indicates that, during peak traffic periods in this control section, the worst traffic condition observed after the signal improvement was better than the best condition observed before signal improvement. The control section of Figure 1, designated as zone 1, is 3.65 km (2.27 miles) in length.

The time costs in Figure 1 were computed by RUNCOST (9). The adopted values for automobiles attempt to take into account the purpose of the trip. Commuter-period trips were assigned a value of $4.80/vehicle/h, off-peak trips during working hours were assigned a value of $3.20/vehicle/h, and leisure-time trips were assigned a value of $1.60/vehicle/h. Values of time to commercial vehicles ranged from $4.66 to $7.77/vehicle/h depending on the size of the truck.

The calculation of operating costs was the principal justification for developing RUNCOST. Time costs are merely a useful by-product and can be obtained without using RUNCOST. If operating costs were very small compared to time costs, there would be little incentive to use RUNCOST. Therefore, the cost-effectiveness of RUNCOST depends in part on the value of time per vehicle per hour adopted for the study. If, for example, values lower than the $4.80, $3.20, and $1.60 reported

in the preceding paragraph were to be adopted, then operating cost would become a larger proportion of the total benefit. The justification for using RUNCOST would increase. The lower the assigned value of time is, the more cost-effective RUNCOST becomes.

The Northside Drive evaluation was conducted during a period of rapidly rising gasoline prices. The RUNCOST program permits the user to apply an inflation factor to adjust the operating costs from the 1969 base level to the current level. A study of the prices of gasoline and automobiles in 1969 and 1975 yielded an inflation factor of 1.32 for Northside Drive. This figure was applied not only to the RUNCOST analyses of the after study performed in 1975 but also to the analyses of the before study in 1973. (If there had been no signal improvement, the before traffic conditions of 1973 would have continued to 1975 and would be paid for by motorists at 1975 prices.)

Figure 1 is derived from floating-automobile runs performed in the through lanes. Left-turn lanes and cross-street approaches at key intersections were investigated as well by using stopped-time-delay studies following the Berry-Vantil method. These supplemental studies showed that the selected approaches also experienced a reduction in costs of operation and time. The savings to through-traffic motorists and to motorists on the selected approaches were summed over a typical week. The weekly savings in vehicle-operating costs amounted to $18 000 or $919 000 annually. The time-cost savings were about twice as large: $36 000/week or $1 833 000/year.

The cost of the Northside Drive signal project was $277 500. The annual savings in vehicle-operating costs alone, amounting to $919 000, are sufficient to repay in triple the project cost to the motorists in the course of a year. If the dollar value of time savings is also considered, the total annual benefits of $2 802 000 amortized the project cost in approximately 1 month.

The RUNCOST analysis also showed that fuel consumption was reduced by 22 percent, a saving of 284 million liters/year (0.75 million gal/year). Pollutant emission was reduced by 38 percent, which amounts to 0.5 kg (1.1 million lb)/year.

SUMMARY AND CONCLUSIONS

1. The original version of the RUNCOST program was developed principally to determine vehicle-operating costs. Time costs are reported as a useful by-product but can be obtained without RUNCOST. Therefore, the lower the assigned value of time per vehicle per hour is, the greater the relative importance of operating costs are and the greater the cost-effectiveness of using RUNCOST is.
2. RUNCOST was first applied to the evaluation of the Charleston, South Carolina, signal-system project. In view of the microscopic and comprehensive treatment of speed changes by RUNCOST, the evaluators concluded that the use of RUNCOST was cost-effective.
3. RUNCOST has since been expanded to include the printout of fuel consumption and pollutant emission. The expanded program was first applied to the evaluation of the Northside Drive signal system in Atlanta. Using the relatively high current prices for gasoline and automobiles and the hourly values of time stated above, we found that the saving in vehicle-operating cost was 50 percent as large as the saving in time cost. Therefore operating-cost savings were not at all insignificant as compared to time-cost savings. When we consider that vehicle-operating costs are much more tangible than motorist time costs, we can readily conclude that the operating-cost capability of RUNCOST is highly effective.
4. RUNCOST was effective in determining the reduction in fuel consumption and pollutant emission for Northside Drive.
5. RUNCOST requires an equipment outlay of approximately $500. No more than 1 person-d of office work at the clerical level would be added to the simplest signal project. Northside Drive, with its three control sections and other complications, required 5 person-d. This office cost amounted to only 5 percent of the evaluation budget. Computer charges are insignificant.
6. These findings indicate that the RUNCOST evaluation procedure is highly cost-effective and should be considered for inclusion in any floating-automobile study of traffic-signal-system improvement.

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