Energy and Emission Consequences of Improved Traffic Signal Systems

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The primary objective of this study was to evaluate the impacts of selected strategies for improvement of traffic signal systems and to develop policy guidelines for the strategies in light of current realities such as increasing passenger delay on surface streets, high costs and scarcity of fuels, and concern about the environment. The existing simulation and optimization model, TRANSYT6C, was applied to a selected study arterial, San Pablo Avenue in Berkeley, California. Two basic categories of traffic signal timing improvement strategies were evaluated: (a) splits and offsets optimization and (b) optimal cycle length selection. A series of sensitivity analyses was conducted to determine variations in the impact effects of the strategies under different operational environments in terms of changed levels of traffic flow. The effects of different objective functions were also investigated and included. The major findings of this investigation include the following. For a given cycle length, optimization of splits and offsets based on either the minimization of passenger delay or fuel consumption also led to near-minimum value for all other measures of effectiveness. Passenger delay and vehicle emission were further reduced by shorter cycle lengths; however, total stops were further reduced by longer cycle lengths. Fuel consumption was relatively less sensitive to changes in cycle length. As the level of traffic flow increased, a moderate cycle length rather than a short cycle length was preferred in order to minimize fuel consumption. Trade-offs between passenger hours saved per gallon of fuel consumed were identified for different cycle lengths and flow levels.

In recent years emphasis in transportation planning has shifted from long-term, capital-intensive, capacity-increasing construction projects to shorter-term, relatively low-cost projects aimed at using existing transportation facilities more efficiently. The importance of energy conservation and environmental impact analysis is also being stressed. This trend in the transportation engineering field placed heavy emphasis on transportation system management (TSM) as a part of the planning process and as a prerequisite for improvements to increase the capacity of the urban transportation system (1). One of the typical elements of TSM planning is optimization of traffic signals in terms of energy saving, reduction in vehicle emissions, and increase in the productivity of transportation systems.

Control of traffic signals is by far the most common type of control at heavily trafficked intersections in urban areas. Inefficient use of the transportation system results when traffic signals are set without the aim of optimizing them. The byproducts of such situations include greater fuel consumption, increased vehicle emissions, increased travel time, higher accident rate, and less reliable services. According to Federal Highway Administration (FHWA) data (2), fuel consumption could be reduced by 100 000 barrels of crude oil per day if the timing of the 130 000 coordinated, signalized intersections that currently exist along the nation's urban streets were made optimum. Thus, signal retiming optimization is regarded as one of the most obvious TSM strategies to implement and one of the most cost-effective energy, pollution, and cost-conservation measures available in transportation.

Signalized intersections can be classified into two types: (a) an individual intersection and (b) a network that is comprised of two or more intersections and streets that link those intersections. For the analysis of individual intersection capacity and performance, the critical movement method (3) is being developed as a part of a National Cooperative Highway Research Program (NCHRP) project. Other useful analytical methods include the U.S. highway capacity manual (HCM) (4, pp. 111-159); British (5), Australian (6), Swedish models (7); the signal operations analysis package (SOAP) (8); and network simulation (NETSIM) (9) methods. For an arterial network that is comprised of a number of signalized intersections, the coordination of traffic signals along the route is regarded as one of the most efficient ways to improve total system performance by reducing delay, stops, fuel consumption, and vehicle emissions. Cycle length, splits, and offsets of traffic signals in the system need to be evaluated and made optimum to improve total system performance.

One of the most important analytical tools of signal time optimization in arterial network is computer simulation. Traffic simulation models can be used to analyze existing conditions as well as to predict the shorter-term and longer-term impacts of traffic control strategies on selected measures of effectiveness (MOE) like fuel consumption, vehicle emission, travel time, and number of stops. In 1973 modeling efforts for arterial networks in terms of signal optimization were initiated by the Institute of Transportation Studies (ITS) of the University of California at Berkeley. A literature review revealed the existence of the traffic network study tool (TRANSYT) (10) model, developed by the British Transport and Road Research Laboratory (TRRL), that could perform similar tasks. Many versions of the TRANSYT model have been developed by various organizations throughout the world to meet their transportation needs. These modified TRANSYT versions include TRANSYT/6 (11), TRANSYT6C (12), TRANSYT/6N (13), TRANSYT/7 (14), TRANSYT7F (15), and TRANSYT/8 (16). The developers and features of several TRANSYT versions are included in Table 1. Although a traffic performance measure such as delay or travel time is often the only impact considered in most versions, the newly arising considerations of traffic management in terms of fuel consumption, vehicle emission, and priority treatment are addressed directly in the TRANSYT6C model. This model is selected for the purpose of this study because emphasis is placed on various impacts evaluations and more flexible objective functions.

TRAFFIC SIGNAL UPGRADING TOOL

Investigation of traffic signal upgrading strategies in the field can be expensive and time consuming. Unexpected and unnecessary congestion may result and cause negative citizen reaction. There is a need to develop and use computer models to evaluate the impacts of various strategies for upgrading traffic signals in different operating environments.

Overview of TRANSYT6C

TRANSYT6C is a macroscopic, deterministic model used to simulate and optimize arterial network signal timings. The model is based on TRANSYT/6 (11), developed by TRRL, and was extended and tested by Clausen, Jovanis, May, Kruger, and Deikman at ITS to include fuel and emission estimates, spatial and

Table 1. Developers and features of TRANSYT versions.

Model	Developer	Date	Features
TRANSYT/1	D.I. Robertson, Transport and Road Research Laboratory	1967	Base model
TRANSYT/2	Transport and Road Research Laboratory	1968	FORTRAN IV rewrite of TRANSYT/1; provision for more than three-stage signals
TRANSYT/3	Transport and Road Research Laboratory	1970	Reorganized data input facilities and checking
TRANSYT/4	Transport and Road Research Laboratory	1971	Allowed the calculation of initial signal settings to equalize saturation; flow pattern graphs added
TRANSYT/5	Transport and Road Research Laboratory	1972	Provided multiple links at a common stopline and bus progression speed and time-at-stops along a link
TRANSYT/6	Transport and Road Research Laboratory	1975	Included an improved model of stops; program could also be more readily compiled on some smaller computers
TRANSYT/6C	P. Jovanis, A.D. May	1977	Fuel-consumption and vehicle-emission estimation, priority treatment, demand response prediction, and improved performance index; U.S. units
TRANSYT/6N	R. Akcelik, National Capital Development Commission	1978	Link groups, intersection statistics, and search for optimal cycle time
TRANSYT/7	Transport and Road Research Laboratory	1978	Cheaper optimization, bottleneck facility added, and input format modification
TRANSYT/7F	C. Wallace, K. Courage	1981	Time-space diagram, fuel-consumption estimation; U.S. terminology
TRANSYT/8	Transport and Road Research Laboratory	1980	Gap-acceptance model, fuel-consumption estimation, monetary costs of delay and stops, preliminary output for the selection of cycle time, and maximum queue length control

Figure 1. Overview of TRANSYT6C model.

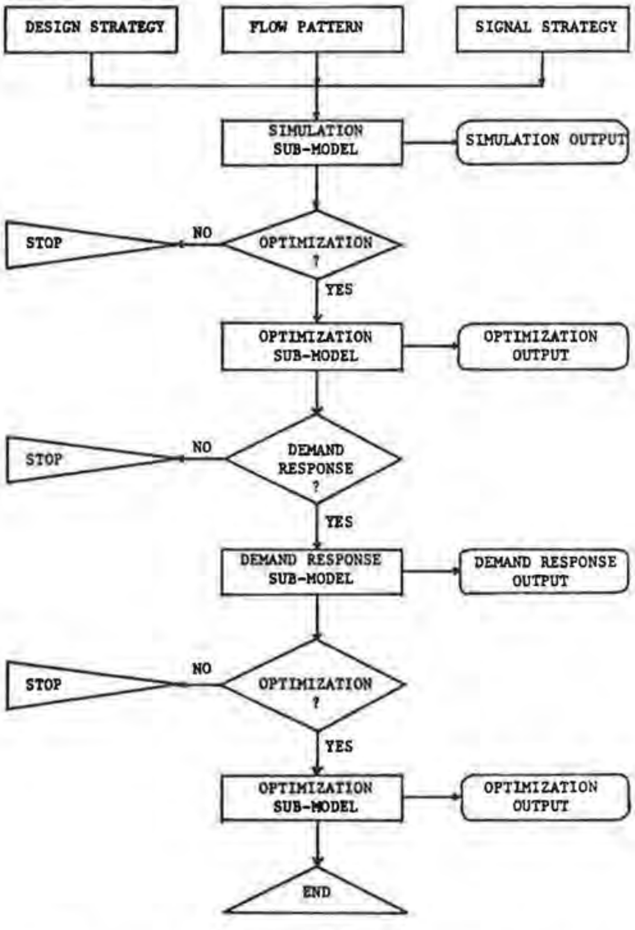
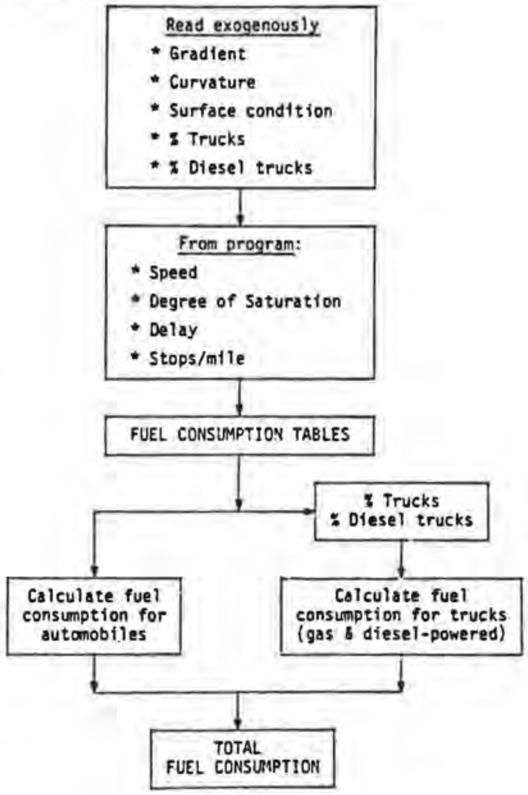


Figure 2. Structure of fuel-consumption submodel.



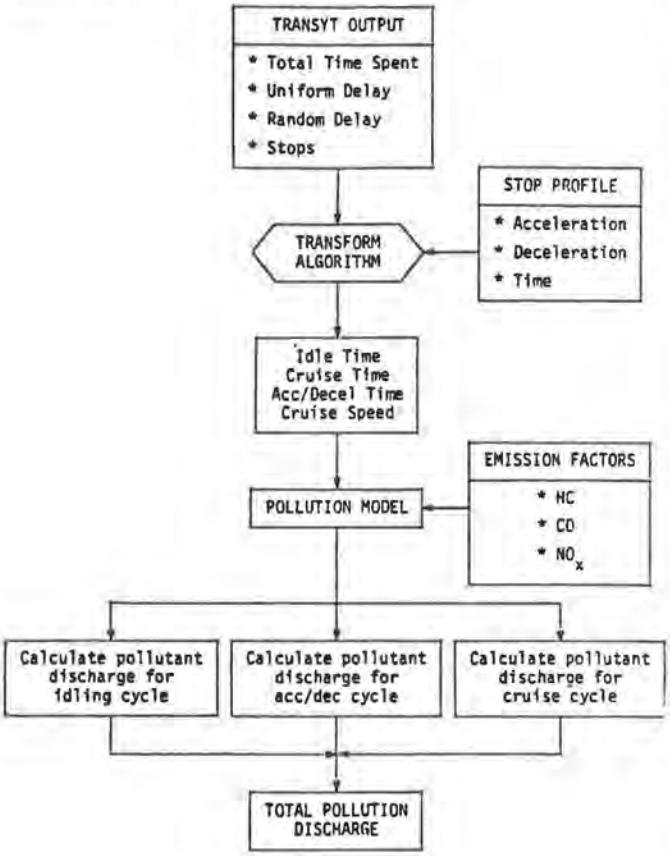
demand responses, and reformulated objective functions. The results of their research have been documented in various papers and research reports (12,17-19).

The program requires as input a description of the roadway design, flow pattern, and signal strategy. The model represents vehicles as platoons that change as vehicles proceed through signals and disperse along a route. The arterial network is represented as a series of nodes (intersections) connected by a series of unidirectional links. It provides as output traffic performance for each link measured by the following variables: estimate of the fuel consumption and vehicle emission impacts, time spent, distance traveled, uniform and random delay, number of stops, maximum uniform queue, and degree of saturation. The individual link values are summed to arrive at measures of system performance. Traffic signal optimization uses hill-climbing techniques that search the response surface for a minimum value of a performance index. After the signals are optimized, the demand response submodel may be engaged. After the demand response occurs, the signals may be optimized again for the new flow conditions. An overview of the TRANSYT6C model is shown in Figure 1.

Table 2. Adjustment factors for change in fuel economy by year.

Year	Factor	Year	Factor
1974	1.000	1981	0.831
1975	1.000	1982	0.791
1976	0.980	1983	0.747
1977	0.955	1984	0.748
1978	0.931	1985	0.670
1979	0.902	1986	0.638
1980	0.871	1987	0.612

Figure 3. Overview of vehicle emission submodel.



Impacts Prediction and Demand Response

Since energy and cost saving is a prime concern, the capability of the TRANSYT model to predict vehicle emission and energy consumption is becoming one of its most important features. With this model, users can generate optimal signal settings that will minimize a weighted formula of fuel, emissions, delay, and stops and also differentiate between priority and nonpriority vehicles. The model can also be used to evaluate alternative design and control plans with reversible lane, priority lane, and one-way street operations.

Fuel Consumption

Energy estimates in the TRANSYT6C model are based on fuel-consumption rates developed by Claffey (20). The tables are entered for each link by using traffic data developed from TRANSYT output and a series of user-specified values that describe geometric conditions. All values between table entries are obtained by linear interpolation. The three driving aspects considered in computation of fuel consumption are cruise, acceleration-deceleration, and stopped time. Additional computations are made to this procedure to calculate fuel consumption for priority vehicle links. Overall structure of the fuel-consumption submodel is shown in Figure 2.

Automobile fuel economy has been improving steadily over the last few years and will continue to improve in the future; therefore, a method of updating the fuel figures in the model may be needed. Based on a California Department of Transportation report (21), annual adjustment factors for fuel economy change by year are shown in Table 2.

According to one of the authors of the report (21), a base year of 1974 is assumed as the year when the average vehicle on the road had fuel economy characteristics similar to those of the Claffey vehicles (20). Use of adjustment factors is simple and no program modifications are required. To update a TRANSYT6C fuel estimate for 1981, for example, multiply it by 0.831.

Vehicle Emissions

An overview of the vehicle emission submodel in TRANSYT6C is shown in Figure 3. Based on a report by Kunselman and others (22) to the U.S. Environmental Protection Agency (EPA), a simplified version of a vehicle emission model was developed and incorporated into the TRANSYT6C model. The model postulates that the amount of a particular pollutant emitted can be computed by multiplying the emission factor for the pollutant by the extent of driving done in each aspect. For each individual link, the three driving aspects considered in calculation of vehicle emission are cruise, idle, and acceleration-deceleration. TRANSYT6C contains separate treatments for automobile and bus links and the additional calculation for bus emissions were included in the model. Individual link emissions are then summed to compute total emissions for the arterial network.

Demand Response

Traffic management strategies may alter an individual choice of route, mode, time of travel, or rate of travel making. The demand responses will result in a change in traffic performance and thus a change in impacts (fuel consumption and vehicle emission). The amount of each type of response depends on the characteristics of the trip, the characteristics of the trip maker, and the characteristics of the transportation system. The TRANSYT6C model applies the general formulation that a response is a function of a stimulus times a sensitivity. The stimulus for demand responses is the change in vehicle travel time computed in TRANSYT6C. The sensitivity reflects the traveler's awareness and opportunity to take advantage of the change in travel time. The sensitivity is user specified and is applied to the submodels of spatial and model demand responses. For the purpose of computing changes in travel time, the study arterial is divided into segments as specified by the user. The segments should correspond as closely as possible to the average trip length (miles) on the arterial. Then, the change in the traveler's trip time for the average trip length is estimated by computing change in travel time for each segment. The demand responses are treated sequentially. A driver is assumed to alter his or her route, if possible, before changing mode.

Performance Index

Today traffic management emphasizes consideration of energy and environmental impacts as well as passenger mobility. In keeping with these new concerns of traffic management, the following performance index (PI) is introduced in the TRANSYT6C model:

$$PI = \sum_{i=1}^{n} [(K_1 d_i)_{NP} + (K_2 S_i)_{NP} + (K_3 f_i)_{NP} + (K_4 d_i)_P + (K_5 S_i)_P + (K_6 f_i)_P + K_7 CO_i + K_8 NO_i + K_9 HC_i] \quad (1)$$

where

- $K_1, K_2, \ldots, K_9$ = weighting factors;
- i = link i;
- n = number of links;
- d_i = delay on link i;
- S_i = stops on link i;
- f_i = fuel consumed on link i (gal);
- CO_i = carbon monoxide emitted on link i (kg);
- NO_i = nitrous oxide emitted on link i (kg); and
- HC_i = hydrocarbons emitted on link i (kg).

NP and P refer to nonpriority and priority vehicles, respectively. By selecting different values for the weighting factors, the user may include or exclude certain variables from the PI. For example, if fuel consumption for priority and nonpriority vehicles is desired in the PI, K_3 and K_6 may be set to one and all other weights set to zero. It is even possible to assign dollar values to each weighting factor and to attempt to set signals to minimize the total cost of the impacts considered. This new performance index permits the direct evaluation of timing signals for energy, emission, and cost savings as well as for traffic performance.

MODEL APPLICATION

In order to test the utility of the TRANSYT model as a tool for upgrading traffic signals and to assist in the development of policy guidelines, the model has been applied to several operational environments. A specific location in the San Francisco Bay Area was used and, through sensitivity analysis, expanded to represent a wide cross section of operational environments.

Site Description and Data Base

In the San Francisco Bay Area, San Pablo Avenue in Berkeley was selected as the study arterial. San Pablo Avenue runs parallel to Interstate 80 in the East Bay and the street is important as an alternate route to travelers on the Eastshore Freeway. It extends from the Oakland central business district (CBD) on the south through Berkeley to Albany, El Cerrito, and Richmond on the north. The street carries two-way operation, three lanes in each direction, on a 74-ft width with no parking on either side at the time of the study. Although the arterial is not heavily congested, it carries a significant number of local buses. The 2.75-mile section on San Pablo used has nine intersections. The representation of San Pablo Avenue used in the TRANSYT6C model application is shown in Figure 4. In the figure the circled numbers represent intersections, and directional arrows represent links.

The study section consists of nine signalized intersections with a common (fixed) 70-s cycle. Because of slightly more critical operational problems, the evening peak hour was selected for the model application. A previous study by ITS (23) developed data to be used in TRANSYT for the study section. Local traffic operations engineers in Berkeley examined the TRANSYT output and agreed that the traffic performance given by the model was a realistic representation of peak-hour conditions (12).

The following characteristics of the study section at the time of the study were used as input to the model: (a) bus flows 13-18 vehicles/h in both directions; (b) average bus occupancy of 30 passengers; (c) average automobile occupancy of 1.2 passengers; (d) vehicle mix of approximately 2 percent trucks and buses, 50 percent of which are diesel; (e) roadway was straight and level; (f) directional split along the study section was approximately 60-40 with predominent flow northbound.

Objective Functions Selection and Optimization

By modifying PI, signal settings may be optimized to satisfy different objective functions. The new PI equation allows a detailed evaluation of impacts and the consequences of different impact objectives. The equations below give traffic management objectives and corresponding PIs employed in the San Pablo study site.

The PI to minimize total passenger delay is

$$PI = \sum_{i=1}^{n} [(d_i)_{NP} + (d_i)_P] \quad (2)$$

Figure 4. Site characteristics.

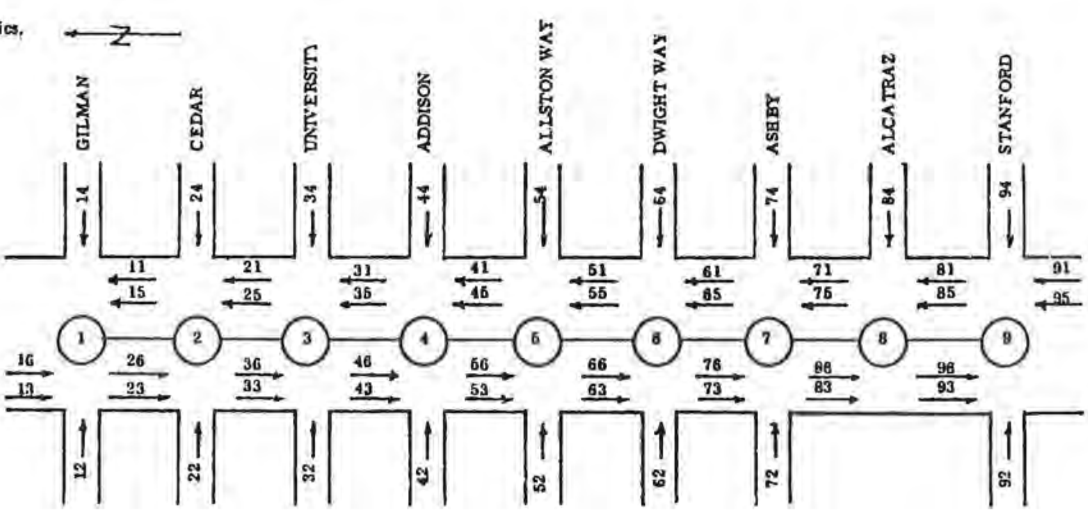


Table 3. Design of experiment with TRANSYT6C.

Flow	Minimization Objective	Run No. for Existing Spacing			Run No. for Half Spacing	
		50-s Cycle	70-s Cycle	90-s Cycle	50-s Cycle	70-s Cycle
Existing	Total delay	1	11	21	31	41
	Priority delay	2	12	–[a]	32	42
	Total stops	3	13	23	33	43
	Total fuel	4	14	24	34	44
	Total emissions	5	15	25	35	45
50 Percent Greater	Total delay	6	16	26	36	46
	Priority delay	7	17	–[a]	37	47
	Total stops	8	18	28	38	48
	Total fuel	9	19	29	39	49
	Total emissions	10	20	30	40	50

Note: Entries in cells are production run numbers.
[a]Run not made.

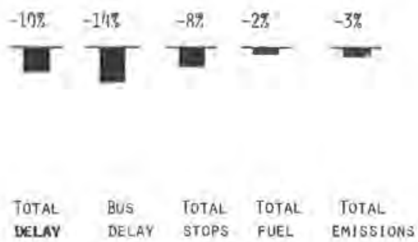


Figure 5. Effect of optimized splits and offsets on reducing impact under existing flow conditions.

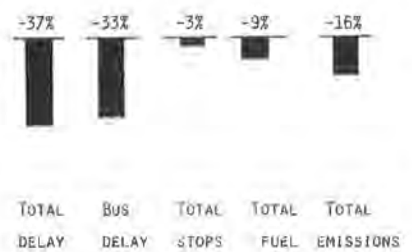


Figure 6. Effect of optimized splits and offsets on reducing impacts under increased flow conditions.

The PI to minimize priority passenger delay is

$$PI = \sum_{i=1}^{n} (d_i)_P \quad (3)$$

The PI to minimize total vehicle stops is

$$PI = \sum_{i=1}^{n} [(S_i)_{NP} + (S_i)_P] \quad (4)$$

The PI to minimize total fuel consumption is

$$PI = \sum_{i=1}^{n} [(f_i)_{NP} + (f_i)_P] \quad (5)$$

The PI to minimize total vehicle emissions is

$$PI = \sum_{i=1}^{n} (CO_i + NO_i + HC_i) \quad (6)$$

where

- n = number of links,
- i = link i,
- d_i = delay on link i (passenger hours),
- S_i = vehicle stops on link i (vehicle stops/h),
- f_i = gasoline consumed on link i (gal/h),
- CO_i = carbon monoxide emitted on link i (kg/h),
- NO_i = nitrous oxide emitted on link i (kg/h), and
- HC_i = hydrocarbons emitted on link i (kg/h).

NP and P refer to nonpriority and priority vehicles, respectively.

In addition to these basic runs with different objective functions, a number of sensitivity tests were performed in terms of different cycle lengths, traffic flows, and signal spacings (although production runs were made for different signal spacings, their results have not been analyzed and are not discussed in this paper) to determine variations in results from the basic runs. Examination of minimum green time due to pedestrian requirements indicated that a 50-s cycle length was the shortest that could be used to the study section. In order to select a cycle length that was equally spaced but greater than the existing cycle length, a 90-s cycle was chosen.

Each of the three cycle lengths was tested under two different flow conditions: existing flows and existing flows increased by 50 percent. Only the cycle length and flow were changed for each specific basic run mentioned above. The impacts for each cycle length after optimization were compared with the impacts for the existing signal timing with the same flow conditions. Table 3 summarizes the design of these sensitivity production runs as well as basic runs.

TRAFFIC SIGNAL UPGRADING POLICY GUIDELINES

Split and Offset Optimization

The results of optimization runs were compared with the existing condition runs in terms of passenger delay, vehicle stops, fuel consumption, and vehicle emissions. Figures 5 and 6 show the effect of optimized splits and offsets on reducing those impacts under existing flow conditions and increased (by 50 percent) flow conditions, respectively. The existing common cycle length of 70 s was employed in both cases.

As can be seen in Figures 5 and 6, all the impacts have been reduced by optimizing splits and offsets of signals along the study network. Under the existing flow condition in Figure 5, the optimization of splits and offsets resulted in 10 percent reduction in total passenger delay (14 percent reduction in bus delay), 8 percent reduction in total vehicle stops, 2 percent reduction in total fuel consumption, and 3 percent reduction in total vehicle emission. The reductions in those impacts by splits and offset optimization under increased flow conditions are greater than those under the existing flow conditions except the reduction in vehicle stops. Figure 6 shows the estimated impacts reduction by the optimization, which ranges from 3 percent reduction in total stops to 37 percent reduction in total passenger delay.

These impact reductions were achieved by adjusting existing splits and offsets in the optimization computer runs to minimize total passenger delay. Although splits are usually set to give equal degrees of saturation to two critical traffic flows at an intersection and offsets are set to give good progression to the traffic flow by manual method, the comparison of the optimized signal timings with existing ones reveals that it might be necessary to give a preference to the predominant traffic flow in terms of splits and offsets to optimize the total system performance. Although the flow in Figure 6 was increased by 50 percent from the existing condition in Figure 5, the impact reductions by optimizing splits and offsets are almost three times those obtained in Figure 5. This result implies that even the best signal timing for the present flow level might not be the best one if the flow level were to change in the future. Therefore, it would be desirable to adjust traffic offsets and splits as the traffic flow level changes in the future, even though the present signal timing has been best optimized for the current flow level.

Cycle Length Selection

Figures 7 and 8 show the effect of cycle length with optimized splits and offsets on reducing impacts under existing flow conditions and increased flow conditions, respectively. Under existing flow conditions, as can be seen in Figure 7, the total delay and emissions were further reduced by employing a shorter cycle length (50 s) while further reductions in total steps were achieved by employing a longer cycle length (90 s). Although Figure 8 also shows this general trend, note that measured impacts reduction are less sensitive to the variation of cycle length under increased flow conditions. Compared with other MOEs, in Figures 7 and 8, fuel consumption seems to be relatively less sensitive to the changes in cycle length. As the level of traffic flow increased, a moderate cycle length rather than a short cycle length was preferred in order to minimize fuel consumption.

Although the optimization of splits and offsets could reduce all the impacts for those three different cycle lengths (except total stops in 50- and 70-s cycle length, and total delay in 90-s cycle length), the figures show that the effect of the change in each cycle length on total delay and emission might be opposite to its effect on total stops to some degree (especially under existing flow conditions, in this case).

Depending on the objective of signal timing optimization, the optimal cycle length can vary from a short cycle to a long cycle length. Generally speaking, a reasonably short cycle length is preferred to a long cycle length to minimize total delay and emissions and vice versa. However, several cycle lengths should be tested by using the computer simulation model and the results should be examined carefully before applying the general effect of cycle length described above.

Objective Function Selection

TRANSYT6C can employ various objective functions by simply modifying PI; therefore, it might be necessary to provide general guidelines for the selection of an appropriate objective function for system optimization. Based on the extensive sensitivity analyses of objective functions, the objective function of either minimizing total fuel consumption or minimizing total delay also reduces all other impacts. Thus, either of them is regarded as the best single objective function. Figures 9 and 10 show the effect of these objective functions on reduction in total delay and total fuel consumption. As can be seen, both objective functions reduced not only total delay but total fuel consumption for different cycle lengths employed.

The differences in the results of the objective functions are regarded as a kind of trade-off between fuel-consumption reduction and total delay reduction. Figure 11 is included to discuss this trade-off in terms of passenger hours saved per gallon given up. For the network under study, from 0.5 to 4.0 passenger-h savings have to be given up to save 1 gal of fuel if one attempts to further reduce fuel consumptions below the fuel-consumption-reduction level achieved by the objective function of minimizing total delay. Depending on the perceived relative value of fuel and passenger hours, therefore, either of those objective functions can be employed to meet the specific objective. Alternatively, the relative values expressed in numerical terms can be assigned to weighting factors of fuel and delay items in the PI, respectively.

SUMMARY AND FUTURE RESEARCH

The primary objective of this study was to evaluate the impacts of selected strategies to improve traffic signal systems and to develop policy guidelines for the strategies in the light of current realities such as increasing passenger delay on surface streets, high costs and scarcity of fuels, and concern about the environment.

The existing simulation and optimization model, TRANSYT6C, was applied to a selected study arterial, San Pablo Avenue, Berkeley, California. The study network consists of nine signalized intersections that have a 70-s common cycle length. Although evening peak hour flow conditions were used as inputs to the study, the network was not heavily congested at the time of study.

Two basic categories of strategies for improvement of traffic signal timing were evaluated: (a) splits and offsets optimization and (b) optimal cycle length selection. A series of sensitivity analyses was conducted to determine variations in the effects of the strategies under different operational environments in terms of changed traffic flow levels. The effects of different objective functions were also investigated and included. The major findings of this investigation include the following.

1. For a given cycle length, optimization of splits and offsets based on either the minimization of passenger delay or fuel consumptions also led to near-minimum value for all other MOE.
2. Passenger delay and vehicle emissions were further reduced by shorter cycle lengths; however, total stops were further reduced by longer cycle lengths. Fuel consumption was relatively less sensitive to changes in cycle length. As level of traffic flow increases, a moderate cycle length rather than a short cycle length was preferred in order to minimize fuel consumption.
3. Trade-offs between passenger hours saved per gallon of fuel consumed were identified for different cycle lengths and flow levels.

Considerable investigations to reduce various impacts have been conducted through the traffic signal timing improvement by using TRANSYT6C, but constraints of time and budget prohibited the further investigation of potentially fruitful areas of research. Future research may be divided into three basic categories: additional model application and sensitivity analyses, model modification and expan-

Figure 7. Effect of cycle length on reducing impacts under existing flow conditions with optimized splits and offsets.

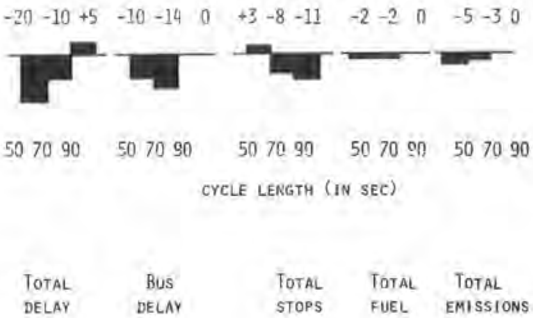
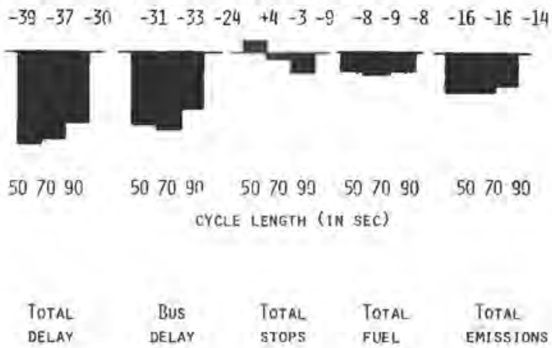


Figure 8. Effect of cycle length on reducing impacts under 50 percent increased flow conditions with optimized splits and offsets.



sion, and development of traffic-responsive signal control system.

Additional model applications include the following:

1. Evaluation of additional traffic management strategies such as bus and carpool lanes or paratransit for various traffic flows that have different composition characteristics;
2. Further testing with the multiple objective function to minimize the total cost of impacts evaluated;
3. Further application of the model to other arterial networks with different characteristics from the study site in terms of geometry, flow pattern, and signal timings; and
4. Sensitivity analysis of improved traffic signal timings to the traffic flow variations such as morning peak flow, evening peak flow, and off-peak flow.

Possible areas for model expansion and modification are as follows:

1. Inclusion of additional impacts such as operating costs, safety, and noise pollution;
2. Inclusion of origin-destination information in the model;
3. Inclusion of additional demand responses such as temporal shift or a change in the rate of tripmaking;
4. Modification of the model to reduce the computing time in large networks and handle bottleneck situations; and
5. Field validation studies in terms of fuel-consumption and vehicle-emission estimation.

A possible area for the development of traffic-responsive signal control systems includes dynamic traffic signal control systems that provide adjustments of signal timings for shortand long-term changes in traffic demand, arterial capacities, and operational conditions. The integration of the greatly improved capability of traffic signal controllers and detectors into the dynamic control system for more effective use of arterial systems is

Figure 9. Effect of objective functions on total delay.

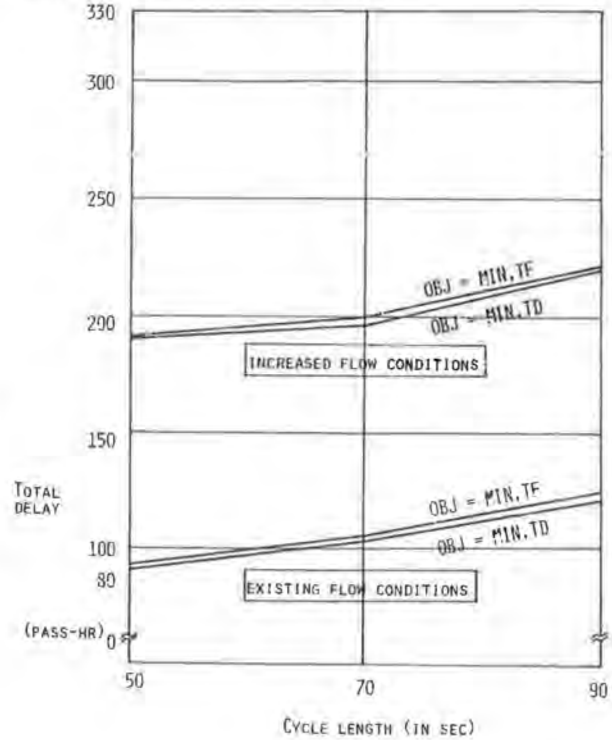


Figure 10. Effect of objective functions on total fuel.

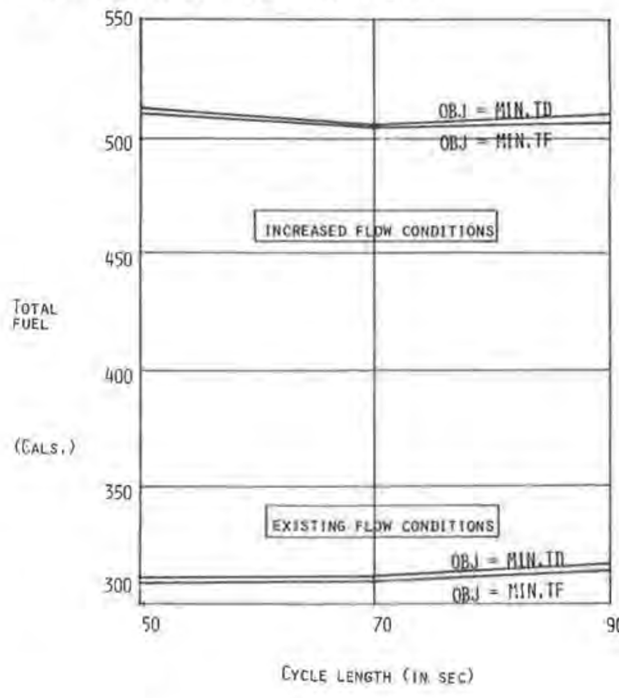
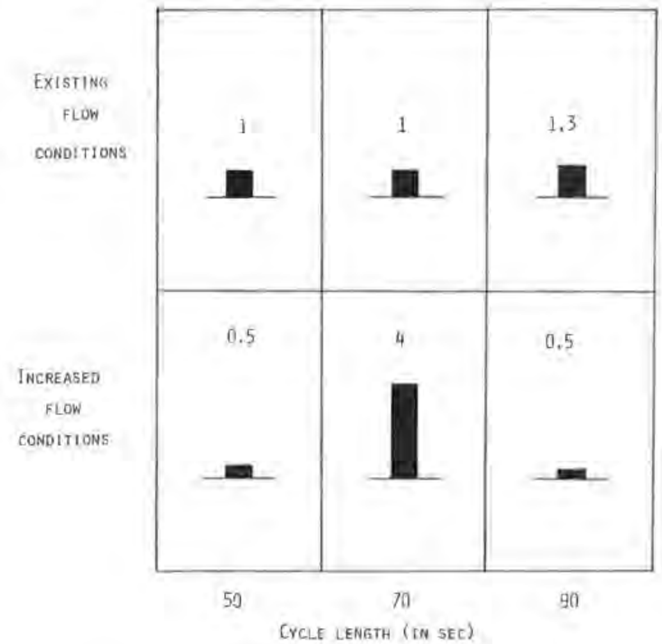


Figure 11. Total delay-total fuel trade-off (passenger hours saved per gallon given up).



another area to be developed.

ACKNOWLEDGMENT

This paper describes and summarizes the results of the study, which used TRANSYT6C, conducted at ITS, University of California, Berkeley. We are indebted to the following former researchers of ITS who have developed TRANSYT6C, applied the model, and made very valuable suggestions and comments on this research: Paul Jovanis of Northwestern University, Thomas Clausen, Abraham Kruger, and Alan Deikman. We also would like to thank Walter Okistu, Victor Siu, and Wai-Ki Yip for their contributions to the computer production runs and the design of experiments with the model. Special appreciation is given to Ken Courage of the University of Florida for pointing out error in the fuel-consumption table (regarding fuel consumed while vehicles are stopped), which have been corrected. Finally, our appreciation is extended to Sylvia Adler for typing this paper.

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