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Reconstructing Major Transportation Facilities: The Case of Boston's Southeast Expressway

MICHAEL D. MEYER

ABSTRACT

With an increased emphasis on the rehabilitation and reconstruction of existing infrastructure, transportation engineers are becoming increasingly concerned about the planning efforts needed to maintain acceptable travel conditions in urban corridors where major reconstruction efforts are occurring. Described in this paper are the reconstruction of a major expressway that serves downtown Boston and the efforts made by the state transportation agency to minimize disruption to expressway users. The actions that were implemented include improved subway and bus service, expanded park-and-ride facilities, increased ridesharing capability, improved commuter boat operations, increased capacity on major parallel routes, and extensive public information dissemination. The results of an evaluation program are used to discuss the effectiveness of each action. These results, combined with similar experiences elsewhere (e.g., Pittsburgh and Chicago), provide useful guidance to transportation officials on the overall approach that should be adopted to minimize disruption during reconstruction efforts. Because large-scale reconstruction usually affects the lives of many people, the political factors associated with such reconstruction can be significant. These factors, as found in the Boston case, are highlighted. Also outlined are the major characteristics of an overall strategy for minimizing disruption during reconstruction projects.

As the highway system ages, transportation planners and engineers are increasingly faced with the challenge of reconstructing major highway facilities in a manner that minimizes disruption to facility users. Described in this paper is a strategy that was adopted by the Massachusetts Department of Public Works (MDPW) to minimize disruption during the reconstruction of a major expressway that serves Boston. The response of expressway users to this strategy, which was determined through surveys and traffic-ridership counts, is discussed in detail. Because the reconstruction of a major urban highway facility is a complex undertaking and potentially controversial, the key characteristics of a successful strategy to minimize disruption to facility users are outlined in the final section of this paper.

PLANNING THE RECONSTRUCTION OF MAJOR TRANSPORTATION FACILITIES

The planning of the reconstruction of a major urban highway is different from the typical transportation planning effort in several ways. First, there are two major groups that will be affected by the reconstruction--the users of the facility and those individuals who live in areas that will experience increased congestion as a result of diverted traffic. The often lengthy time needed to generate public interest in the construction of new facilities is considerably reduced in reconstruction efforts where the reconstruction is viewed as an immediate and dramatic threat to existing travel behavior. The responsible agency must therefore be prepared to deal with the issues that are likely to be raised by both groups--issues that could easily conflict with each other. For example, providing alternate routes for diverted traffic (an objective of facility users) can easily conflict with minimizing traffic congestion in adjacent communities (an objective of nearby residents).

Second, the types of actions that need to be considered in reconstruction planning range from those that require physical construction (e.g., park-and-ride lots) to changes in institutional behavior (e.g., variable work hours). A wide range of skills is necessary to implement a successful strategy that includes such diverse actions. Because these skills are seldom found in one individual, reconstruction planning requires the coordinated effort of numerous agencies and transportation professionals and, most likely, a formal coordinating mechanism such as a task force.

Third, the time frame for reconstruction planning is much more limited than that for most other projects. Whereas new construction projects can sometimes be in the planning stage for 3 or more years, planners concerned with reconstruction issues usually have, at the most, 1 year before the reconstruction begins. The impact of this short time frame is greatest on the analysis methodology that is used to assess alternate courses of action. Throughout the planning effort, but especially in the latter stages when the public begins to realize that the project will soon occur, planners must have an analysis capability that produces reliable information quickly. Analysis will not only be necessary on the impacts of the reconstruction on alternate routes and modes, but important policy issues (such as the banning of trucks) will likely surface throughout the planning process. The need for a quick response to these types of issues suggests that the analysis methodology must rely mainly on existing data bases, and use relatively uncomplicated and unsophisticated modeling techniques.

A recent conference on the future of travel analysis methods concluded that gaining a better understanding of the effects of reconstructing major facilities was one of the important issues likely to face transportation professionals in the next 5 years (1). There is little information in the literature on how temporary travel disruptions affect travel behavior and how facility reconstruction should be planned. Most technical articles have focused on construction-related activities such as safety (2,3) or on the overall economic benefits of the reconstruction project (4). More recently, attention has been given to the operations plan that was needed to divert traffic during short periods while maintenance activities were undertaken (5). The type of literature that came closest to reconstruction planning was that on contingency planning (6,7). However, these articles were mainly concerned with addressing sudden temporary transportation disruptions.

It was not until the Federal Highway Administration sponsored a demonstration project on the reconstruction of a major expressway in Pittsburgh that substantial documentation was available on the characteristics of reconstruction planning and of traveler response (8,9). The documents produced during this project were important for their contribution to understanding what happened in Pittsburgh, but left unanswered questions about how such planning should occur elsewhere and how different circumstances might influence the effectiveness of mitigating actions.

These characteristics of reconstruction planning, and the still little-researched phenomenon of traveler response to major construction disruption, will be further examined in the following case study of expressway reconstruction in Boston.

RECONSTRUCTION OF BOSTON'S SOUTHEAST EXPRESSWAY

Boston's Southeast Expressway is the only major highway facility that connects Boston with the rapidly growing southeastern part of Massachusetts. Originally designed in the late 1950s to handle an average daily traffic volume of 75,000 vehicles, the Expressway was carrying more than 160,000 vehicles daily by 1983. This substantial increase in volume was the result of rapid growth in the communities that were served by the Expressway and a highway construction ban which, in 1970, stopped most major highway construction in the metropolitan area. A major expressway 6 miles away that was intended to carry a large portion of the Boston-bound traffic was never built, thus causing most highway traffic from the south of Boston to use the Southeast Expressway. During the period that followed the highway ban, however, a rapid rail transit line was extended south parallel to the Expressway. Other means of transportation in the corridor, all of which serve the Boston commuter, include several commuter boat lines, two commuter rail lines, numerous public and private bus services, and a regional ridesharing program.

In 1982 the MDPW found that the 15 bridge decks on the Expressway were in various stages of deterioration. Within 2 years these bridge decks would have to be replaced, an effort that would cause serious disruption to the users of the Expressway. The reconstruction of the bridge decks, however, was viewed by MDPW engineers as an opportunity to make other improvements to the roadway, including resurfacing the entire length of the road in a way that would not add substantially to the level of disruption likely to be caused by the bridge construction. Thus in March 1983, the MDPW began the reconstruction of 8.5 miles of the Southeast Expressway. The reconstruction, which would last until November 1985, would not only involve replacement of the bridge decks and resurfacing of the roadway, but would also involve

1. Improvement of vehicle access and egress at selected ramps through widening and lengthening of merge areas;
2. An increase in safety measures through provision of more effective emergency turnouts, lighting the entire length of the Expressway, and encouraging more consistent road signing; and
3. Elimination of serious drainage problems that existed in several locations along the roadway.

Because such reconstruction would likely cause serious disruption to Expressway users, MDPW engineers undertook two major efforts that were designed to minimize disruption. First, given that the Expressway was such an important highway facility that served large numbers of people, the MDPW wanted to provide as much capacity on the Expressway during the reconstruction period without hindering its ability to finish the project as quickly as possible. It was decided that the 6-lane Expressway (with two breakdown lanes that are used as travel lanes during the rush hours) was to be divided into four sections of two lanes each. The reconstruction would begin on the outside two lanes on the northbound side with the remaining two lanes serving northbound traffic at all times. The southbound roadway was divided into two parts with 8.5-miles of barriers. The two lanes between the barriers and the Expressway median were reversible lanes, northbound between the hours of 5:30 a.m. and 12:00 p.m. and southbound between 1:00 p.m. and 10:00 p.m. The remaining two southbound lanes served southbound traffic at all times (Figure 1).

By designing the traffic management scheme this way, MDPW engineers were able to provide the same number of lanes in the peak hour direction during the project as there was before, although the capacity would likely decrease because of barrier constraints and the "curiosity factor" of construction that occurs so close to the roadway. When the two lanes under construction were finished, the next two northbound lanes would be closed to traffic and the finished lanes opened to traffic.

The second effort by MDPW engineers was to prepare a comprehensive plan for minimizing disruption to Expressway users. The actions in this plan were selected on the basis of several criteria that included

1. The degree to which the action will provide opportunities for Expressway users to use alternative modes, routes, or times;
2. The feasibility of implementation within the time span before reconstruction;
3. The cost effectiveness from the point of view of the action's contribution to minimizing disruption per dollar expended;

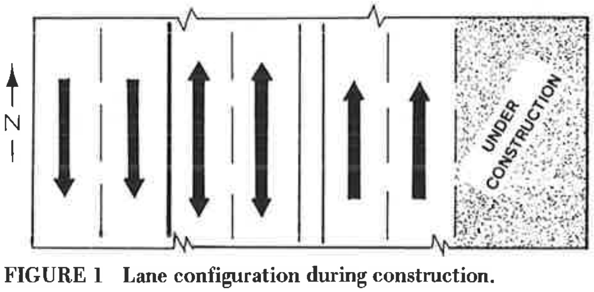

FIGURE 1 Lane configuration during construction.

4. The contribution of the action to more permanent transportation improvements after the reconstruction was completed; and
5. The flexibility of removing the action that was found to be ineffective.

ACTIONS TO MINIMIZE DISRUPTION DURING EXPRESSWAY RECONSTRUCTION

The types of actions that were implemented to minimize disruption ranged from construction projects to operational improvements. The overall cost of these actions was about $9 million.

Park-and-Ride Lots

The MDPW is responsible for the park-and-ride program in the Commonwealth of Massachusetts and, in this capacity, had constructed several parking lots (1,600 spaces) throughout southeastern Massachusetts. In anticipation of the reconstruction, the MDPW expanded two lots, built three more, and leased space for a sixth, adding a total of 1,500 spaces to the park-and-ride capacity that serves the Expressway. Each of these lots was to be served by public or private bus service. In addition, the MDPW subsidized the expansion of five parking lots (300 spaces) at commuter rail stations.

Ridesharing

A private, nonprofit corporation was established in 1978 to organize long-distance commuter vanpools as an alternative to the single-passenger automobile, and, up to 1983, it served more than 1,800 commuters in 135 vans throughout the state. Because of the reconstruction project, this corporation was asked to establish an employer-based ridesharing program and create an information brokerage program that would be the focal point for all information on transportation options in the Boston metropolitan region. For the first time, Boston commuters could call one phone number to obtain information on public and private bus services, commuter rail services, commuter boat operations, ridesharing options, and park-and-ride locations.

Alternative Routes

Experience from other cities that faced reconstruction projects indicated that one of the predominant means of commuter response was to find alternate highway routes to the destination. In anticipation of such behavior, MDPW engineers identified four major routes that would serve as likely diversion routes, and located key congestion points along these routes. Working with local officials, MDPW engineers were able to make signal and pavement marking improvements at 29 intersections.

Mass Transit

As mentioned previously, the Expressway corridor was served by several mass transit modes. Unfortunately, the subway line that serves the corridor was already at capacity during rush hours, and the major commuter rail line experienced ridership at 140 percent of seating capacity during several peak hour departures. The mass transit component of this program therefore focused on adding temporary capacity to the fixed rail system and on implementing new bus services. By doubling rail departures on the southern commuter rail lines, an additional 2,200 passenger seats would be available to commuters. The public transit agency also made agreements with eight private bus operators to provide express bus service from key communities in southeastern Massachusetts. A total of 30 buses were added to peak hour service. In addition, two new commuter boats were subsidized for operation from a town 10 miles south of Boston.

Variable Work Hours and Flextime

Another means of adapting to disruption found in other reconstruction projects was commuters changing their departure time to avoid major delays. The MDPW, in cooperation with the transit agency and the Boston Chamber of Commerce, sponsored a major conference to encourage large employers to implement a variable work hours or flextime program. It was expected that large government agencies would initiate such programs to set an example.

Police Enforcement

Officials from communities adjacent to the Expressway indicated great concern that overflow traffic would create serious congestion and safety problems in the neighborhoods through which alternate routes traveled. The MDPW, in cooperation with local police agencies, identified numerous intersections where police enforcement of traffic regulations and directing of traffic might be necessary. A multiphased strategy of placing police officers at 68 intersections during the first 2 weeks, at 31 intersections for the subsequent 3 weeks, and then at those intersections where clear problems existed, was agreed to by the state and local police authorities.

Local Community Assistance

The state devoted most of its resources to regional transportation services, that is, the provision of bus, boat, and rail services that could be used by commuters throughout the affected area. In meeting with local officials, however, it became apparent that there would be several local sites such as transit terminals where increased traffic caused by the reconstruction would likely increase congestion. The department set aside $500,000 to fund proposals from communities that would help mitigate these congestion problems. Fifteen proposals were funded, including the provision of local ridesharing assistance, additional police at terminal sites, expansion of town park-and-ride lots, newspaper advertising, and shuttle bus service to a commuter boat terminal.

Public Information and Community Liaison

A critical component of the mitigation plan was to make available as much information on alternatives as was feasible. Three staff members were hired to lead the public information effort that included radio and television advertisements, the production of public information materials, newsletters, slide shows, and the holding of more than 200 meetings. Utility companies voluntarily published 100,000 brochures on the project and enclosed them with monthly billings. One major corporation produced a videotape on the project to be shown to its employees and loaned to any other interested corporation.

In addition to these actions, the department also required the construction contractor to provide four tow trucks that would be able to handle breakdowns and accidents, and incorporated into the contract a clause that provided a $10,000 per day bonus if the job were finished before the project deadline. To minimize congestion and to avoid a potentially dangerous accident situation, large trucks were also banned from the reversible lanes. Because of the difficulty in enforcing this ban, numerous meetings were held with trucking associations to seek their voluntary compliance.

COMMUTER AND COMMUNITY RESPONSE TO EXPRESSWAY RECONSTRUCTION

The characteristics of commuter and community response to the reconstruction during the first 3 months is discussed in the following sections. This response was determined through a comprehensive data collection effort that included screenline traffic counts, license surveys, on-board ridership questionnaires, and household mailback surveys.

Traffic Volumes

In the weeks leading up to the reconstruction, the local media reported daily on the concerns of public officials, businessmen, and Expressway users with regard to the economic, social, and political impacts of the reconstruction. As a result of this attention, in addition to numerous warnings from the MDPW's public information effort, there were 7,000 fewer cars on the Expressway during the first week of reconstruction than there were in previous weeks (Figure 2). A major consequence of this decrease in traffic was a much improved traffic flow on the Expressway itself. By the third week of reconstruction, a vastly improved Expressway flow (and extensive media attention) began to attract large numbers of vehicles back to the Expressway.

Overall, the Expressway experienced a 9-percent decrease in traffic in the northbound direction (about 5,000 vehicles) between the hours of 6:00 a.m. and 7:00 p.m. when adjusted for seasonal variation. In the southbound direction, the decrease was close to 3 percent during the same period. During the morning 3-hr peak period, the average reduction in traffic has been about 1,500 vehicles.

The average time to travel northbound between 7:00 and 9:00 a.m. on the Expressway decreased by 4 min for commuters in the reversible lane section and by 3 min for commuters in the remaining two lanes. In the southbound peak, the time saving was 1 min for the reversible lane and 1.5 min for the remaining two lanes. The average automobile occupancy did not change significantly from that before the reconstruction.

Not surprisingly, the alternate routes to Expressway travel experienced heavier travel when Expressway volumes were down. These routes showed various degrees of impact that ranged from a 20-percent increase to a 4-percent decrease from traffic volumes before the reconstruction. In addition, traffic counts showed that a larger portion of traf-

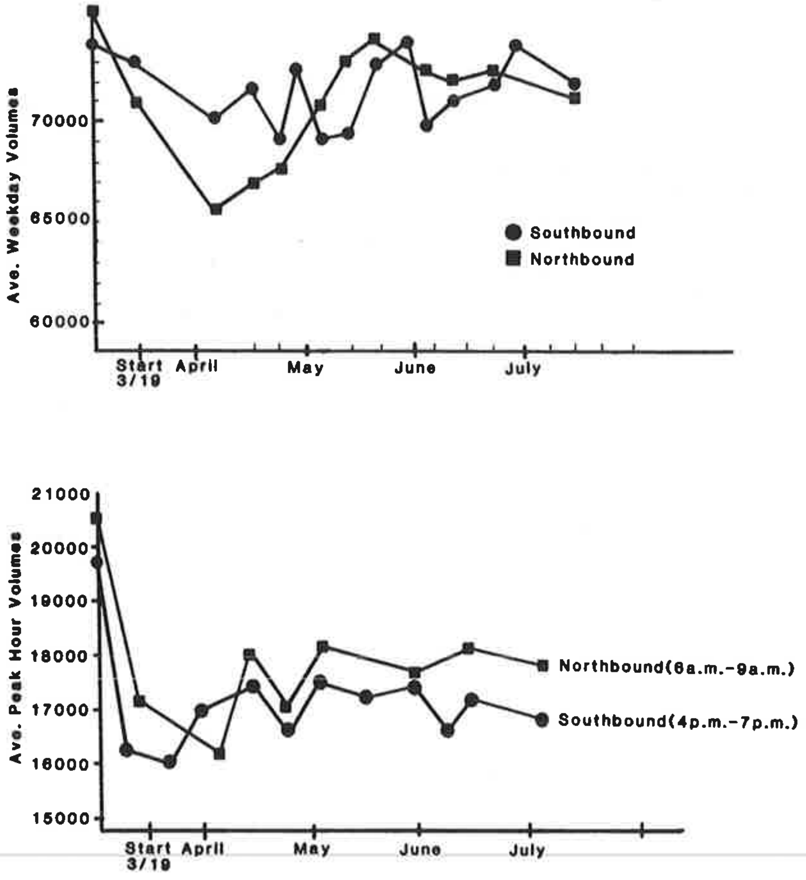

FIGURE 2 Average weekday and peak hour traffic volumes.

fic was on these routes in the first hour of peak hour travel (6:00 to 7:00 a.m.) than was the case before reconstruction. Thus, although the alternate routes did experience additional traffic, this traffic was spread over the entire 3-hr peak period and did not create any serious congestion problems. Further, the travel time needed to travel each of the five major alternate routes decreased, thus indicating that the traffic management actions implemented by the MDPW were successful.

With regard to trucks, 2 months after the reconstruction began, the overall number of heavy trucks decreased by 600. On the two alternate routes that closely paralleled the Expressway, the increase in heavy trucks was 330. On a percentage basis, the largest decrease in the number of trucks occurred during the hours of 1:00 to 3:00 p.m., that period in which only two lanes were available in the northbound direction.

Park-and-Ride

Vehicle counts were taken at 16 park-and-ride-sites 1 month after reconstruction began and showed an increase of 7 percent in parked vehicles from before the reconstruction. A user survey was conducted at each of the 16 lots, and 41 percent (700) of the surveys were returned. Close to 7 percent of those surveyed were new users of the lot who had come from Expressway vehicles, and 4 percent had come from other lots. The majority of the respondents (78 percent) were using the lot 5 days per week. Of particular interest was the mode used by the commuters after leaving their car at the lot--14 percent carpooled, 14 percent vanpooled, 13 percent used a commuter boat, 33 percent used bus service, 22 percent used commuter rail, and 4 percent indicated that they used other means.

Commuter Boat

The number of riders who used commuter boats fluctuated widely during the period following the beginning of reconstruction. During the second week of reconstruction, boat ridership had increased by 225 passengers. By the following week, this increase had declined to 130 passengers, and by the beginning of July (3.5 months after reconstruction began) ridership had increased by 350 passengers. The difficulty with interpreting this data is that several factors, including seasonal variation and the addition of new service, can explain this increase in ridership. The best indication of how many Expressway commuters were attracted to commuter boat service is obtained from a ridership survey that was conducted 1 month after reconstruction began (10). About 260 passengers (a 70-percent response) responded to this survey, which indicated that 15 percent of the respondents (40) were using the service for the first time because of the reconstruction. Of this number, 60 percent used a car as their primary means of transportation before switching to commuter boat.

Commuter Buses

The extra commuter buses that were subsidized by the department, in general did not experience a significant increase in ridership. The change in ridership on individual routes ranged from a 33-percent increase to a 34-percent decrease. The most successful express service was initiated from Brockton, a city 30 miles south of Boston, to a rapid transit terminal that provided direct service to Boston. This service showed an increase of 260 passengers per day 1 month following the beginning of reconstruction. In general, and excluding the Brockton express service, commuter bus ridership, when seasonally adjusted, increased by 4 percent.

Because it had been anticipated that some of the bus service might not be cost-effective, the department and the regional transit authority agreed to review these services every 3 months. Twenty-three bus runs were discontinued after the first 3-month evaluation that was based on the criteria that each run have at least 15 passengers and not cost more than $3.50 per passenger. Fifteen bus runs were continued.

Commuter Rail and Rapid Transit

During the first several weeks of reconstruction, the most heavily used mass transit alternative was the additional commuter rail service. Ridership increased by about 1,000 passengers after the second week of reconstruction. By the second month of reconstruction, the number of new riders who used commuter rail had reached a fairly stable level of 400 passengers per day. In addition, the number of cars parked at the commuter rail stations had increased by 200 cars.

The change in ridership on the subway line that served the affected corridor did not change significantly when adjusted for seasonal variation. During the month of April, a period that encompassed 2 to 6 weeks after the beginning of reconstruction, the overall change in ridership during the morning peak period was an increase of 600 passengers. In May the ridership declined by 500 passengers and in June there was little difference between the observed and expected ridership.

The previous discussion indicates that the commuter response to the reconstruction occurred across several modes and alternate routes. To better determine this response, a license plate survey was conducted in which close to 6,000 questionnaires were sent to Expressway-user households whose address was determined from license plate registrations. Of these, 595 valid responses were obtained. The results of this questionnaire provide some interesting information on the dynamics of commuter response. Because the questionnaire was sent to those who had used an automobile during the day of the license plate survey, one can assume that most of the respondents usually used their car for travel. Of the 595 respondents, 208 (35 percent) indicated that they had tried an alternate means of transportation during the 2 weeks before and after reconstruction began. Of these, 53 (25 percent) tried the subway, 19 (9 percent) commuter rail, 22 (11 percent) express bus, 15 (7 percent) commuter boat, 107 (51 percent) drove on an alternate route, and 11 (5 percent) rode as a passenger on an alternate route. (Note: percentages do not total 100 because of rounding.) Of particular interest is that 65 percent of the respondents did not change their behavior because of the reconstruction and stayed on the Expressway, and the most common commuter response was to try an alternate route.

In addition to this information on commuter response, the questionnaire also contained a request for respondents to list up to three sources of information that they were exposed to on alternative means of travel. The responses to this request are summarized in Table 1. It is interesting to note that the normal means of information--radio, television, newspapers, and word of mouth--were the pre-

TABLE 1 Sources of Information on Alternate Means of Transportation

Sources	Respondents
Newspaper	345
Radio/television	300
Word of mouth	158
Pamphlet	82
Poster	33
Community meetings	13
Telephone information line	7

Note: Respondents were asked to list no more than three sources.

dominant sources of information. Much of the information presented by the media was provided by the MDPW's community liaison-public relations effort for the Expressway reconstruction.

DEVELOPING A STRATEGY FOR MINIMIZING RECONSTRUCTION DISRUPTION: LESSONS FROM THE SOUTHEAST EXPRESSWAY

There is little question that the reconstruction of major transportation facilities can cause tremendous disruption to an urban area. Not only are there concerns about maintaining commuter mobility during the reconstruction period, but adjacent residential and commercial interests often become rightly concerned about significant impacts of diverted traffic. Given these concerns, the responsible agency must develop an effective strategy for approaching the likely disruption and for communicating information on the project and on the mitigating actions to affected interest groups.

On the basis of the Southeast Expressway experience, there are several important characteristics of commuter response to major reconstruction and of a successful mitigation strategy.

Understanding Likely Commuter Response

The dynamic nature of commuter response to such disruption can be observed in the fluctuation of the number of vehicles that use the Expressway throughout the reconstruction period. For example, in the 3-hr evening peak period (southbound) during the first 2 weeks of construction, the average traffic volume was 16,500 vehicles. By the fourth week of construction, and after 2 weeks of media attention on how easy the Expressway commute was, the average traffic volume for this 3-hr period was 17,500 vehicles. This change caused a perceptible increase in the level of congestion in the southbound peak direction which, along with media attention on the worsening situation, resulted in an average volume during this 3-hr period for the following 2 weeks of 16,400 vehicles. During the next 2 weeks, the average volume increased to 17,600 vehicles, where it stayed for 4 weeks. Not surprisingly, the fluctuation of traffic volumes on alternate routes and ridership on alternative modes was opposite that of the Expressway, increasing when volumes decreased on the Expressway and vice versa.

The importance of this fluctuation was that it was symptomatic of an important characteristic of commuter response to travel disruption--there appeared to be a period of adjustment in which commuters tried alternative actions to decide which was the best coping strategy. Thus, there was a pendulum effect of traffic coming back to the Expressway when travel conditions were good, and leaving when conditions worsened. This phenomenon continued until the second month of construction when some form of equilibrium was established. It is during this initial reaction period that providing information on alternative means of travel is critical.

Identifying Agency Objectives

The reconstruction of major transportation facilities is often subject to conflicting agency and community objectives. The responsible agency will most likely want to complete the project as soon as possible, which usually means restricting the use of the facility. Such restrictions, however, mean diverting traffic elsewhere--a diversion that can create significant problems in other areas unless they are anticipated and steps are taken to mitigate the impact.

The responsible agency must face this trade-off between speed of construction and traffic diversion early in the planning process. In the case of the Southeast Expressway, every attempt was made to handle as much traffic as possible on the Expressway itself (i.e., the reversible lanes), and to discourage commuters from using alternate routes. In anticipation of diverted traffic, the MDPW made traffic engineering improvements and provided traffic police at key bottleneck points, but these routes were neither advertised by the MDPW nor signed as detour routes. Instead, a comprehensive alternative mode program was developed and advertised as the major means of avoiding the disruption.

Implicit in the agency objectives for project construction is the overall philosophy toward the mitigation program. In Boston, the $9 million spent on mitigating actions was considered as much a cost of the project as the physical construction activities (Table 2). And although several analyses were conducted before construction, which indicated the likely commuter response to the disruption, MDPW officials believed that the best approach to minimizing disruption was to provide a wide range of options for commuters (even though some of these options were not considered cost-effective), and then to cut back services that were not being used after 3 months. Not only did such an approach deal with the uncertainty associated with predictions of commuter response, it also appealed to interest group pressure on the various options implemented.

TABLE 2 Budget for Mitigating Actions

Mitigating Actions	Budgeted Amount ($ thousand)
Express bus subsidy	1,230
Local bus subsidy	680
Commuter rail subsidy	3,900
Commuter rail parking	280
Commuter boat subsidy	1,010
Transit police	72
Traffic police	400
Traffic engineering improvements	200
Public information	250
Park-and-ride lots	1,000

Maintaining Program Flexibility

Because many of the mitigating actions were costly to implement, MDPW officials believed it was important to implement them in such a way that would allow their being discontinued if found to be ineffective. Flexibility was thus a key characteristic of program implementation and was found especially in the provision of bus services and police traffic control. Bus service was provided through 3-month contracts with private bus operators. If, at the end of the 3 months, a service had not attracted a sufficient number of riders and no actions could be taken to increase ridership, the service was to be discontinued. Of the 38 bus departures initially subsidized by the department, 23 were discontinued after the first 3-month review. Extensive police presence at key intersections was provided at the beginning of the project with a gradual reduction in force over a 5-week period. At the end of this period, department engineers and local police officials determined together where police officers would continue to direct traffic.

The flexible approach to program implementation appeared to have two important consequences. First, it permitted the department to adjust its resources in a timely fashion to provide the most cost-effective actions once it was clear how commuters were responding to the disruption. Second, it showed local communities and politicians that the department was willing to adjust its mitigating action program to meet needs as they arose. This willingness prompted numerous local officials to work closely with MDPW officials to monitor impacts and to suggest action that they deemed necessary.

Providing Public Information

Given the objective of providing as many options as possible to Expressway users, the department's second objective was to publicize these options and to provide a mechanism for dealing with public and media input. The public information program included newsletters, numerous community meetings, television and radio announcements, newspaper supplements, more than 100,000 brochures and utility bill supplements, and a telephone hotline. Two professionals were hired to act as a community liaison before and during the project, and they spent much of their time in community meetings explaining the project and providing feedback to project engineers on actions that should be considered in project design. These professionals attended all project meetings and participated in discussions at all levels on the mitigating action program.

No matter how extensive the department's public information campaign was, the day-to-day coverage by local media was considered to be one of the most important means of disseminating information to the public. Three major local newspapers published newspaper supplements that outlined alternate modes and routes to Expressway travel, and in one case, even provided schedules of all bus departures in the affected area. Special efforts were made to explain the project to editorial boards, which resulted in the publication of numerous editorials in support of the project and urged commuters to seek alternative means of travel.

Overall, the MDPW budgeted close to $250,000 for public information. On the basis of public and political response to the project, the activities associated with this effort were probably the most critical component of the success of the project.

Coordinating Organizational Action

A project of the magnitude of the Southeast Expressway reconstruction will often require the coordinated effort of numerous agencies, usually at different governmental levels. In the Boston case, the MDPW worked closely with the Massachusetts Bay Transit Authority (the regional transit authority), state and metropolitan police, a regional ridesharing agency, port authority, turnpike authority, and about 15 cities and towns that were affected by the reconstruction. To handle the extensive coordinating effort, a task force was established that met periodically to discuss progress and to identify specific actions that needed to be taken to overcome implementation barriers. This task force not only provided an opportunity for other agencies to discover what was being planned for the project, but it also provided an opportunity for different groups inside the department to coordinate their efforts. For example, the task force was used by engineers from the construction, traffic engineering, design, and planning divisions as an important mechanism for exchanging information on what each was doing for project design and construction.

The value of this task force became most apparent in a disagreement between the police agencies and the MDPW over an accident management strategy for the reconstruction project. The task force was viewed by the heads of each agency as the appropriate mechanism for resolving the basic issues, and after three meetings, a consensus was reached.

Providing Technical Information

Because of the often controversial nature of large-scale reconstruction projects, agency and political decision makers want to have up-to-date information on traveler response to the project and the likely explanation for such response in a timely manner. In the Boston case, there was a substantial demand for information on traffic volumes (both on the expressway and on parallel routes), transit ridership, vehicle occupancy, accidents, and travel time comparisons almost immediately following the beginning of construction. In anticipation of this demand, the MDPW developed an extensive travel monitoring program to obtain information before, during, and for evaluation purposes, after the Expressway project. The schedule for these data collection activities is shown in Figure 3.

Planning and Analysis for the Reconstruction

The nature of a reconstruction project is such that predicting commuter response through analytical means could be a complex undertaking. Several technical analyses were undertaken for the Expressway project, which resulted in 22 technical reports. However, the analysis methodology for these efforts was uncomplicated, relying heavily on origin-destination data from previous surveys and on highway capacity analysis procedures. No effort was made to predict, through demand estimation techniques, which alternatives would most likely be used by Expressway commuters. Instead, capacity analyses were undertaken on alternate routes and modes to determine their additional carrying capacity and to identify key bottlenecks or constraints to handling additional demand. This analysis approach fit closely the overall philosophy of the planning effort that was to provide as much additional capacity as possible.

Even with this simple analysis style, several important characteristics of the analysis process merit special attention. First, although the experiences of other urban areas are important in determining the likely effectiveness of alternate actions, each travel corridor has its own set of

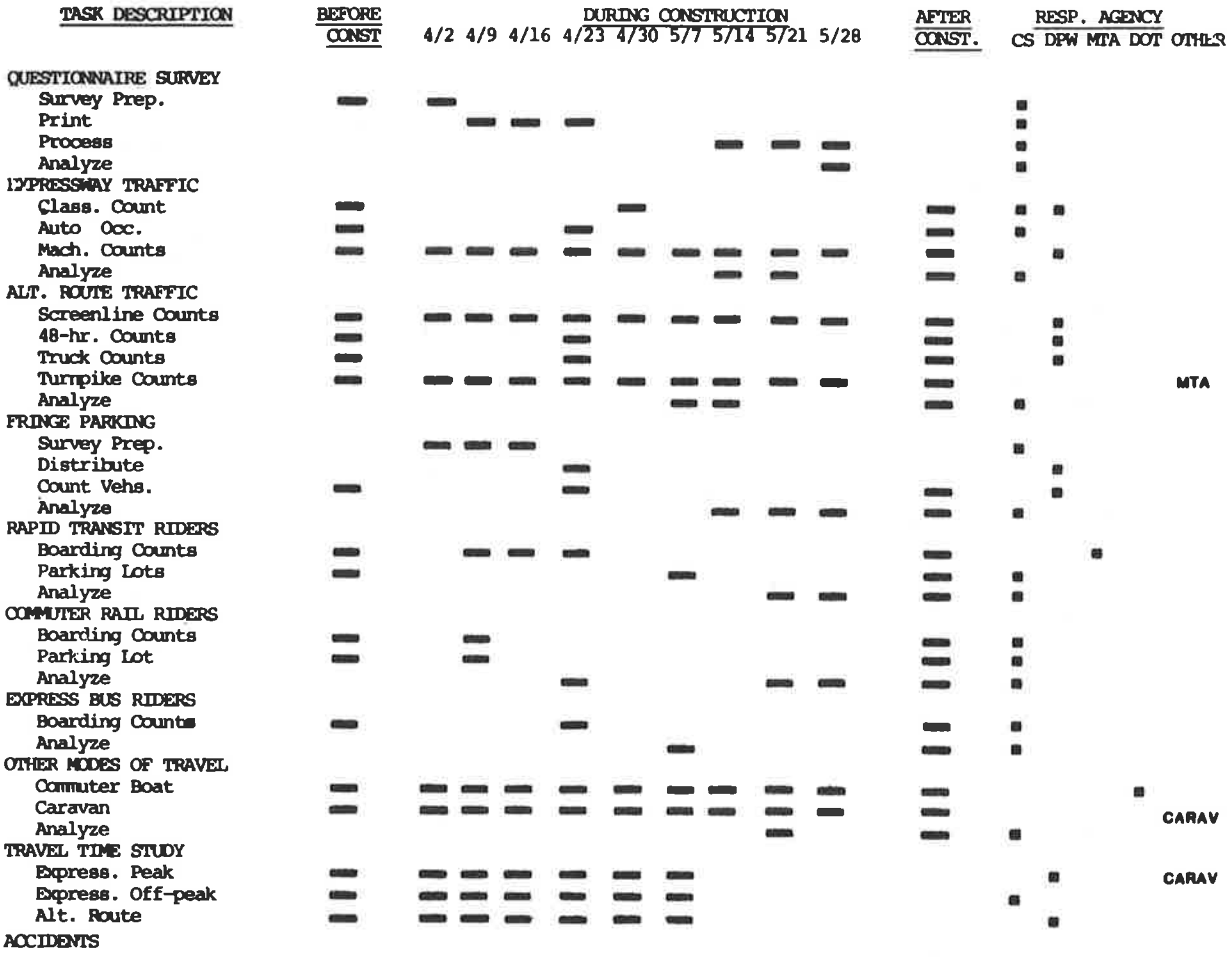

FIGURE 3 Data collection activities for expressway monitoring.

travel behavior characteristics. For example, one result of the Pittsburgh demonstration was the seeming ineffectiveness of the commuter rail service. In Boston, with a well-developed commuter rail system in the affected corridor, the commuter rail service was the most effective alternative mode.

Second, a distinction needs to be made between the immediate (first 2 or 3 weeks) response to the disruption and the equilibrium that is reached when facility users become used to alternative means and routes of travel. The analysis process needs to examine both the short- and long-term response to major disruption.

Third, once construction begins on a major facility, unexpected events can lead to pressure for changes in the strategy to minimize disruption. The analysis process must have the capability to provide quick response to requests for information on the likely impacts of implementing alternative strategies. For example, after a major truck accident on the Expressway caused substantial delays during an evening rush hour, the department received considerable pressure to ban trucks from the Expressway. Within 48 hr, an analysis of truck travel, and of the available alternate routes, convinced decision makers that such a course of action was not feasible.

Although the analysis in the Boston case was not that sophisticated, it was able to provide the information desired by decision makers in a timely and effective manner. It thus served a most important role in developing the department's strategy for handling the disruption.

CONCLUSIONS

The reconstruction of Boston's Southeast Expressway is an example of the type of major facility reconstruction that is facing several North American cities. As observed in the Boston case, the strategy adopted to minimize disruption to the commuter can often be quite comprehensive and complex. In Boston, this strategy included:

1. Added capacity to park-and-ride lots;
2. Additional bus, boat, and train services;
3. Traffic engineering improvements along alternate routes;
4. An increased emphasis on ridesharing and flexible work hours;
5. Increased enforcement along alternate routes;
6. A comprehensive and extensive public information campaign; and
7. Careful traffic management on the construction site itself.

The results of the evaluation effort showed that commuters responded quite dramatically to the media attention on the anticipated disruption of the reconstruction. The most important means of alternate travel was an alternative route, and the most-used mass transit option was commuter rail. The perceived success of the Expressway project was greatly influenced by a comprehensive public information and media effort that provided extensive information on the project and on alternative means of travel.

Although the Boston experience can be considered unique to the circumstances of the Expressway reconstruction, several observations on this experience appear applicable to other situations. The dynamic nature of commuter response to disruption indicates that the initial reaction period (likely to be from 2 to 4 weeks in duration) is an extremely important transition period in which it is paramount that information be provided on what is happening with the project and on the alternative means of travel available. In addition, the responsible agency must clearly identify the objectives of the strategy, and the overall philosophy it will follow in developing a mitigation plan. The resulting plan must be flexible in its implementation to allow the removal of ineffective actions in a timely fashion. The responsible agency must also establish an institutional mechanism for coordinating the action of numerous agencies. With regard to information, a program of data collection is needed to provide the information necessary to modify the mitigation strategy and to answer questions that will surely arise from communities that are affected and the media. Perhaps most important, a comprehensive community relations-media program is essential to the success of any program to minimize disruption.

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Effects of Ramp Metering with HOV Bypass Lanes on Vehicle Occupancy

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ABSTRACT

The concept of providing preferential treatment for high occupancy vehicles on metered freeway on-ramps is being tested for the first time in northern California, as a cost-effective means of reducing freeway congestion. The purpose of this research project was to evaluate the impacts of ramp meter bypass lanes on the traffic system, and on vehicle occupancy in particular. A comparison of before and after project mean occupancy rates and an analysis of covariance revealed a 0.015 person per vehicle increase in automobile occupancy for the ramps with bypass lanes, and a 0.014 person per vehicle decrease for the ramps without bypass lanes. However, it is suspected that these results are mostly explained by a shift of existing carpools from the nonbypass ramps to the ramps with carpool bypass lanes. Another important discovery revealed that bypass lanes and ramp metering can actually be counterproductive to one another. Ramp metering smooths out the congestion, which decreases the carpool incentive, and unless the geometrics of the project are carefully planned, the vehicles that use the bypass lanes can interfere with the ability of the ramp meters to reduce mainline congestion. Although new carpool information was negligible, the tendency for automobile occupancy to increase where the carpool bypass lane incentive is implemented cannot be ignored. The possibility for greater reductions in vehicle miles traveled as a result of the bypass lanes in the future is quite strong if increased traffic congestion enhances the time savings incentive.

Ramp metering is a transportation system management (TSM) technique whereby vehicles that are in the process of entering a freeway during periods of high use are spaced so as to reduce freeway congestion and allow traffic to move faster and more smoothly. Metering makes it possible for more vehicles per hour to use a freeway corridor with an overall shorter commute time. Bypass lanes for high occupancy vehicles (HOVs) at metered ramps allow carpools, vanpools, buses, and other HOVs to bypass single occupancy vehicles that are waiting at ramp meter signals to enter the freeway. They therefore also allow for increased efficiency (i.e., reduced congestion) of the exiting freeway system in terms of people-carrying capabilities by providing an incentive for more people to rideshare (that is, carpool, vanpool, buspool, or use public transit).

Although preferential lanes for HOVs at metered ramps had been in operation for a decade in Southern California, ramp metering was new to the Sacramento area when this first ramp meter project was installed in 1983. Before the project was implemented, congestion had increased on Route 50 to the point where traffic frequently slowed and occasionally came to a standstill. The California Department of Transportation (Caltrans) proposed ramp metering as a cost-effective method for reducing freeway congestion.

Through ramp metering with bypass lanes, several specific traffic issues can be addressed, such as maintaining free flow of traffic, increasing vehicle occupancy, and reducing parking needs in high employment areas. However, the Sacramento Highway 50 Ramp Meter Auto Occupancy Study focuses on the incentive to shift to an HOV mode of travel that this type of project provides. The study was initiated to evaluate the concept of preferential treatment of HOVs at metered ramps in a medium-sized metropolitan area. This paper contains the results of the study, in which the impact of the bypass lanes on vehicle occupancy was evaluated and a discussion on some of the other impacts of the bypass lanes on other aspects of the traffic system.

RELATED LITERATURE

The amount of literature in the general subject area of preferential treatment of HOVs is growing rapidly; however, this paper is not intended to be an exhaustive literature review. The literature discussed here is that which is most pertinent to this study.

Relatively few ramp meter projects with bypass lanes have been rigorously evaluated. Most of the studies that have been conducted conclude that the HOV bypass lanes on metered ramps do not lead to significantly increased vehicle occupancy rates. Goodell, in his evaluation of carpool bypass lanes in the Los Angeles area, indicated that the increase (or decrease) in carpools after installation of the ramp meters with bypass lanes varied from ramp to ramp (1). The time savings for carpoolers who used the ramps with carpool reductions was very short and hardly an incentive to form carpools from existing ramp traffic.

In Goodell's study, two ramps were surveyed to determine the number of additional carpools that had been formed since installation of the carpool bypass lanes. Based on these two surveys, 50 percent of the additional carpools were formed since the installation of the carpool lane. Goodell assumed that all (575) of these new carpools were formed as a result of the project.

Uematsu's report, Evaluation of Preferential

Lanes for High Occupancy Vehicles at Metered Ramps, is an evaluation of the preferential treat- ment of HOVs at metered ramps along the Golden State Freeway (I-5) corridor between Route I-10 and State Route 170 in the Los Angeles area (2). Included in the study were analyses of before, after, and control section data to determine the effectiveness of the preferential bypass lanes. On 13 of the 47 metered freeway on-ramps, bypass lanes were provided for buses and carpools with two or more occupants. The time saving was small, and Uematsu concluded that although the number of carpools had increased, the increase that was attributable to the meter bypass lanes was not considered significant.

Rothenberg's Project Status Report contains a discussion on the current status of 14 preferential treatment projects for buses and carpools in the United States (3). A range of projects is covered, including bypasses of metered freeway ramps. Rothenberg concluded that the increases in carpool use of the Los Angeles area metered ramps was more a result of a route shift by existing carpools than the formation of new carpools.

Rothenberg also documented the status of the I-35 corridor ramp meter project in Minneapolis. He stated that the project is operationally sound; however, the limited travel time savings has resulted in a negligible modal shift to HOVs.

Benke wrote that the provision of preferential treatment for carpool vehicles that use the TH 65 route from downtown Minneapolis did not result in a measurable increase in the number of carpools (4). The delays encountered at the metered entrance ramps were not great enough to induce many carpoolers to divert to the bypass, nor to form new carpools so that they could use the ramp. Primary use of the bypass ramp was by previously existing carpoolers who found it convenient to divert.

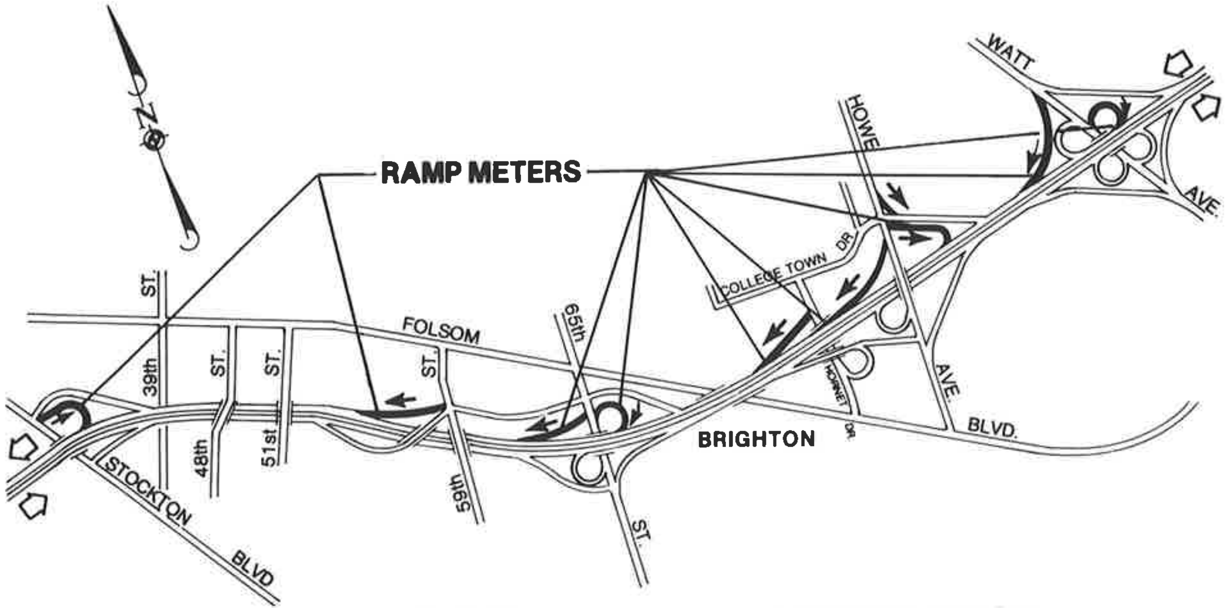
In the San Francisco Bay area, carpools (three or more persons per vehicle) and buses are given priority and toll-free access to the Bay Bridge. The metering system and relatively quick response to incidents provides a generally delay-free ride on the bridge. Currently, about 20 percent of the westbound vehicles that use the bridge between 6:00 and 9:00 a.m. are HOVs. The time savings provided by the HOV lanes at the toll plaza has caused a large increase in the total number of carpools. However, a significant portion of this increase is a result of "casual" carpools formed by drivers picking up passengers at transit bus stops so they can proceed through the toll plaza without delay. These carpools do not reduce vehicular demand for the bridge (5).

PROJECT DESCRIPTION

In the spring of 1982, the $727,000 project was initiated to install ramp meters along the 5-mile Route 50 transportation corridor at westbound on-ramps from Watt Avenue westbound to the Business Route 80 interchange just west of Stockton Boulevard. There are nine metered ramps, four of which have bypass lanes. Figure 1 shows the location of the metered ramps and bypass lanes.

Along with the installation of computer-operated traffic signals at these ramps, a fifth westbound freeway lane was constructed between 59th Street and Stockton Boulevard. The southbound Watt Avenue on-ramp has two metered lanes plus a bypass lane. The bypass lane on the Hornet Drive on-ramp is for buses only. In general, there are four lanes in the westbound direction along the project corridor, but there are portions where there are five--between Stockton Boulevard and 59th Street, and between 65th Street and Howe Avenue. The morning peak commute period usually lasts from 20 to 30 min and occurs between 7:00 and 8:00 a.m.

The speed of the traffic during the morning commute varies. If traffic is running smoothly, it



Stockton Blvd. Ramp
◇ 59th Street Ramp
Southbound 65th Street Ramp
Northbound 65th Street Ramp
◇ Hornet Drive Ramp

Southbound Howe Avenue Ramp
◇ Northbound Howe Avenue Ramp
◇ Southbound Watt Avenue Ramp
Northbound Watt Avenue Ramp

◇ Indicates Bypass Lane For Vehicles Of 2 Or More Persons

FIGURE 1 Highway 50 transportation corridor—westbound on-ramps.

flows at about 40 mph. If there is an accident, stalled car, or other special problem, speeds drop to around 15 to 20 mph. The most congestion occurs around Watt Avenue where the ramps merge into the mainline and in the outside lane (lane No. 4) near Stockton Boulevard. Just east of the Stockton Boulevard on-ramp, vehicles start moving over to the outside lane to get on Business Route 80 East, which is immediately west of the study area. The weaving of these vehicles with vehicles that are merging onto Highway 50 from the on-ramp causes the bottleneck.

The system monitors operate only from 7:00 to 9:00 a.m. on weekdays. The meters are traffic-actuated, meaning that the traffic is monitored between 7:00 and 9:00 a.m., and the meters turn on and off as indicated by the traffic volume. The meters are usually activated from 7:15 to 8:00 a.m. The carpool requirement for use of the bypass lanes is two or more persons per vehicle.

DATA COLLECTION

All "before" traffic count data were collected between April 20, 1982 and May 25, 1982, approximately 1 year before the ramp meters became operational. The "after" counts were made from March 27, 1984 through April 25, 1984, approximately 1 year after the ramp meters became operational. No data were collected on Mondays, Fridays, weekends, holidays, or days of inclement weather. All westbound access ramps on Route 50 from Watt Avenue to Stockton Boulevard were sampled. Counts were also made of the westbound mainline traffic at locations both east and west of the project.

A field crew was trained to make vehicle occupancy counts, both of the ramps and the mainline traffic. Vehicle occupancies were observed and tabulated vocally using portable cassette tape recorders. Ramp counts were made in 10-min intervals from 7:10 to 8:20 a.m. (seven time periods). Mainline lanes were counted for six, 5-min time periods from 7:15 to 7:30 a.m. and from 7:40 to 7:55 a.m. One-hundred percent of the vehicles were counted within each time period. Seven vehicle type categories were defined: automobile, van, motorcycle, recreational vehicle, pickup, truck, and bus. For each vehicle observed, the vehicle type and number of occupants were recorded. For buses, the number of occupants was recorded as either empty (driver only), quarter-full, half-full, full, or standing room only. Altogether, 62,195 observations were recorded.

DATA ANALYSIS

For each observation, the location, date, day of the week, time period, vehicle type, number of occupants, and the name of the data collection crew member who made the observation were documented. Then the average vehicle occupancy was computed for each location before and after the ramp metering project.

The data were analyzed to determine:

1. The difference in before and after project vehicle occupancy rates for each location,
2. The change in the proportion of HOVs for each location observed, and
3. How important an incentive the carpool bypass lanes are to carpool formation.

Changes in Vehicle Occupancy Rates

To more directly address the home-to-work commute during the morning peak period, occupancy rates for vehicle type 1 (automobile) only were compared. The data in Tables 1 and 2 summarize the automobile occupancy rates in descending order by location. The differences in those occupancy rates were calculated, and are summarized in Table 3. The overall increase in the automobile occupancy rate for the ramps with carpool bypass lanes was 0.015 persons per vehicle. That is a 1.3 percent increase for these ramps. This represents an overall small change in automobile occupancy. However, separate examination of each bypass ramp indicates that persons per vehicle increased more significantly for the high traffic volume ramps (northbound Howe Avenue and southbound Watt Avenue). The rate on the low-volume 59th Street ramp was the only carpool bypass ramp where automobile occupancy decreased. The automobile occupancy rate decreased 0.014 persons per vehicle on the nonbypass ramps. This represents an overall 1.2 percent decrease for these ramps.

Although changes in the automobile occupancy rates were very small, these results must be examined in terms of other, exogenous factors that affect the level of carpool participation along the corridor. The price of gasoline declined steadily for 8 months before the "after" data collection

TABLE 1 Locations in Descending Order by Average Automobile Occupancy Rate for Before Project Data

Ramp to Westbound Highway 50	Occupancy Rate (persons/ vehicle)	Mainline	Occupancy Rate (persons/ vehicle)
Northbound 65th Street	1.281		
Northbound Watt Avenue	1.280		
		East Lane 3	1.259
		West Lane 2	1.248
		West Lane 1	1.243
		West (overall)	1.237
		West Lane 3	1.232
		East Lane 2	1.221
		East Lane 1	1.215
Hornet Drive	1.209		
Northbound Howe Avenue	1.209		
		West Lane 4	1.204
		East (overall)	1.198
59th Street	1.186		
Southbound Watt Avenue	1.180		
Southbound Howe Avenue	1.173		
Southbound 65th Street	1.161		
Stockton Boulevard	1.138		
		East Lane 4	1.116

TABLE 2 Locations in Descending Order by Average Automobile Occupancy Rate for After Project Data

Ramp to Westbound Highway 50	Occupancy Rate (persons/ vehicle)	Mainline	Occupancy Rate (persons/ vehicle)
Northbound 65th Street	1.247		
Northbound Howe Avenue	1.239		
Northbound Watt Avenue	1.234		
		East Lane 2	1.210
Southbound Watt Avenue	1.205		
		West Lane 2	1.191
		East Lane 3	1.180
Hornet Drive	1.180		
Stockton Boulevard	1.175		
Southbound 65th Street	1.172		
		East (overall)	1.170
		West Lane 1	1.169
		West Lane 3	1.168
		East Lane 1	1.168
		West (overall)	1.165
Southbound Howe Avenue	1.162		
59th Street	1.142		
		West Lane 4	1.117
		East Lane 4	1.114

TABLE 3 Change in Automobile Occupancy Rate on Carpool Bypass Ramps, Noncarpool Bypass Ramps, and Mainline

Locations	Before (persons/ vehicle)	After (persons/ vehicle)	Difference (persons/ vehicle)
With carpool bypass			
Northbound Howe Avenue	1.209	1.239	+0.030
Southbound Watt Avenue	1.180	1.205	+0.025
59th Street	1.186	1.142	-0.044
Overall	1.186	1.201	+0.015
Without carpool bypass			
Hornet Drive	1.209	1.180	-0.029
Southbound Howe Avenue	1.173	1.162	-0.011
Stockton Boulevard	1.138	1.175	+0.038
Northbound Watt Avenue	1.280	1.234	-0.046
Northbound 65th Street	1.281	1.247	-0.034
Southbound 65th Street	1.161	1.172	+0.011
Overall	1.210	1.196	-0.014
Mainline westbound			
East of project	1.198	1.170	-0.028
West of project	1.237	1.165	-0.072
Overall	1.225	1.168	-0.057

period (6). This decline in gasoline prices, plus the fact that the ramp metering increased flow on the mainline (reduced congestion), would suggest decreased occupancy rates, and mainline automobile occupancy rates did decrease. But automobile occupancy actually increased slightly overall for the on-ramps with the carpool bypass lane incentive. Rates on the ramps without this incentive decreased as expected, even on the high-volume ramps.

The results of t-tests are not given for the differences reported in Table 3. Because of the large number of observations in the sample, the changes in automobile occupancy are assumed to be real, and not a result of sampling variation. Statistical tests of significance would not be meaningful to this analysis, as they would account for only a very small portion of the variation.

Preferential treatment for buses is provided on each of the three ramps that have carpool bypass lanes. In addition, there is a "buses only" lane on the Hornet Drive ramp. No measurable effect of the bypass lanes on bus ridership was discovered. In the sample, bus occupancy increased an average of one person per bus for the HOV bypass ramps as a group. However, bus occupancy decreased by nine persons per bus on the Hornet Drive ramp. Bus occupancy actually increased more on the ramps where no HOV lane exists. Ridership counts conducted by the local transit agency indicated that transit bus ridership decreased during the study period (Sacramento Regional Transit, unpublished data). This decrease was largely attributed to a fare increase that was implemented in July 1983. These results are consistent with the analysis of the mainline data, which show that bus occupancy decreased an average of eight persons per bus. Although these results are inconclusive, it is clear that the HOV bypass lanes did not provide enough of an incentive to induce a significant increase in transit ridership. On the other hand, it cannot be determined if, as a result of the bypass lanes, fewer people quit using public transit in response to the fare increase.

HOV Volume Changes

Another approach taken to measure the level of ridesharing participation along the corridor was to compute the percentage of HOVs that were observed in the sample for each location. The figures were computed by using the automobile, van, pickup, and bus vehicle types. The results are summarized in Table 4. The northbound Howe Avenue, southbound Watt Avenue, and southbound 65th Street ramps exhibited the greatest proportional increases. The three ramps with carpool bypass lanes showed a greater overall increase in the proportion of HOVs entering the freeway than the other six ramps. These results are consistent with the results from the analysis of the change in automobile occupancy rates. The increase in the proportion of HOVs occurred despite an increase in freeway volume between the before and after traffic counts.

TABLE 4 Ridesharing Participation Along Highway 50 Corridor Before and After Ramp Meter Project

	High Occupancy Vehicles	
Location	Before (%)	After (%)
Ramps with carpool bypass		
Northbound Howe Avenue	10.9	18.1
Southbound Watt Avenue	14.4	16.5
59th Street	17.5	15.0
Total	14.4	16.6
Ramps without carpool bypass		
Hornet Drive	17.5	14.6
Southbound Howe Avenue	15.4	14.8
Stockton Boulevard	15.1	15.1
Northbound Watt Avenue	20.4	21.6
Northbound 65th Street	23.2	20.3
Southbound 65th Street	11.8	14.7
Total	17.4	17.5

Importance of the Bypass Lanes

At this time, the preferential lanes do not provide enough of an incentive to induce more people to use public transit, according to the data collected for this survey. However, it is difficult to conclude whether the changes in automobile occupancy on the freeway on-ramps are a result of the presence or absence of carpool bypass lanes. There certainly are other factors that influence a person's decision to carpool. Following is a list of some of these factors:

1. Gas prices;
2. Parking costs and availability;
3. Energy conservation attitudes;
4. Work hours;
5. Availability, cost, and convenience of alternate forms of transportation;
6. Economic conditions of individuals;
7. Type and size of automobile driven;
8. Commute distance;
9. Human behavioral effects such as privacy, independence, and status;
10. Residence and work locations; and
11. Before and after work use of automobile for pleasure, child care, shopping, and so forth.

Many of these influences are known to have changed during the study period, and it is expected that these changes would affect the level of ridesharing participation. However, it is reasonable to assume that the commuters on all the ramps were exposed to these other changing factors equally, so it would be expected that the automobile occupancies for each ramp would be affected in the same way. Occupancy rates, in fact, did not even change in the same direction for each ramp. Because increases in automobile occupancy were shown for some ramps and decreases were shown for others, there must be some characteristic(s) specific to each ramp that influences commuters' mode choice.

To investigate the importance of the carpool bypass lanes as having a significant effect on automobile occupancy rates, the method of least squares was used to fit a general linear model. The model formulated for the analysis is given in Equation 1.

$$\#\mathrm{OCCUP} = \beta_0 + \beta_1 \mathrm{VEHFLO} + \beta_2 \mathrm{METER} + \beta_3 \mathrm{HOV} + \beta_4 \mathrm{V{*}M} + \beta_5 \mathrm{V{*}H} + \beta_6 \mathrm{M{*}H} + \epsilon \qquad (1)$$

where

#OCCUP = the dependent variable, number of occupants per automobile;
VEHFLO = continuous independent variable, a measure of congestion (vehicle flow) on the ramp;
METER = discrete independent variable that represents the presence or absence of ramp metering;
HOV = discrete independent variable that represents the presence or absence of a carpool bypass lane on the ramp;
V*M, V*H, M*H = the interaction effects between vehicle flow and metering, vehicle flow and HOV bypass lanes, and metering and HOV bypass lanes, respectively.
β_0 = the intercept;
$\beta_1, \beta_2, \ldots, \beta_6$ = the regression coefficients of the independent variables; and
ε = the error term.

T-tests for significance of the estimates for the coefficients fail to reject the hypothesis that $\beta_i = 0$, where $i = 1,2,\ldots,6$. In other words, the independent variable for each test has no influence on the mean number of occupants. These independent variables are not separately relevant factors in the prediction of average automobile occupancy for each ramp. However, the F test rejects the hypothesis that $\beta_i = \beta_j = 0$ for $i = 2$, $j = 3$ and $i = 1$, $j = 2$. The separate contributions of ramp metering, bypass lanes, and congestion to the explanation of the variation of automobile occupancy are weak, whereas their joint contributions are quite strong. According to the sample, ramp metering alone did not affect automobile occupancy. Further, increases in automobile occupancy were not observed even when carpool bypass lanes were used in conjunction with ramp metering unless congestion was also a significant factor. Unless congestion causes traffic to back up in the metering queue, there is no time savings incentive for use of the bypass lane. Even with a preferential lane for carpools, if a vehicle can gain access to the freeway just as quickly by using the nonbypass lane, then the advantage of the bypass lane disappears.

The analysis of the changes in automobile occupancy and number of HOVs showed increases for the ramps with HOV bypass lanes where traffic congestion was significant. This appears to indicate that the ramp meters and bypass lanes do provide an effective TSM solution for reducing freeway congestion. The regression model further supports this conclusion. But these analyses are not totally conclusive. It is not clear that there has been an incentive for new carpool formation. A shift has traditionally occurred from other nearby ramps and city streets when HOV bypass lanes are introduced, so decreases in the number of HOVs on the ramps that do not have bypass lanes are not surprising. If this shift has occurred, it could explain the increase in the number of carpools on the ramps with bypass lanes. Perhaps existing carpools have changed routes to take advantage of the bypass lanes. If this is the case, then the carpool bypass lanes cannot necessarily be credited with providing an incentive for new carpools to form.

Although a formal license plate survey was not conducted, it is strongly suspected that this type of shifting occurred from the southbound Howe Avenue ramp (no HOV bypass) to the northbound Howe Avenue ramp with a bypass lane, and possibly between other ramps too. When the ramp meters were installed, a left-turn pocket was added at the intersection of Howe Avenue and College Town Drive (Figure 1) to allow vehicles southbound on Howe Avenue access to the Howe Avenue on-ramp, which was previously accessed only by northbound traffic. It is therefore reasonable to suspect that the increase in HOVs on the northbound Howe Avenue ramp (now also accessed by southbound traffic via a left turn) and the decrease on the southbound Howe Avenue ramp is a result of previously existing carpools shifted from the use of one ramp to the other to take advantage of the bypass lane.

The main thrust of this study has been to evaluate the impact of HOV bypass lanes on automobile occupancy. But in carrying out the study, it became obvious that bypass lanes in a ramp meter project have impacts on the traffic system that extend beyond automobile occupancy. In theory, the potential benefits of providing bypass facilities on metered on-ramps are difficult to argue, but in actuality, there are some drawbacks that should be considered. Several more important observations that concern the bypass lanes were made on the Highway 50 project. They are itemized briefly.

1. Experience has not shown significant new carpool formations as a result of the bypass lanes.
2. Outside the metering period, the bypass lane is frequently used as a short passing lane. This is an unnecessary pass, as the freeway is only a few seconds away and not crowded at this time.
3. The HOV lanes create problems that interfere with the ability of the meters do their job. For ramps that have an HOV lane, the metering rate for the meter lane must be adjusted (longer cycles) to allow for vehicles that use the HOV lane. Also, the percentage of single-occupant vehicles that use the HOV lane varies from 10 to 50 percent, with the higher percentage occurring on the low-volume ramps. Law-abiding users of the metered lane are penalized with a slower metering rate to compensate for the violators. Without strict enforcement, it is anticipated that the percentage of violaters would increase quickly. Some of the single-occupant vehicles make unsafe lane changes into the HOV lane when they are approaching the signal. Some vehicles must radically adjust their speed to merge with vehicles that are leaving the signal in the metered lanes. Another problem occurs when vehicles in the bypass lane fill the gaps between metered vehicles. When this happens, it is more difficult to merge onto the mainline because a solid line of traffic from the on-ramp will be entering the already occupied outside freeway lane. This eliminates the beneficial aspect of the scattered vehicles that enter the freeway.
4. The cost is relatively high to provide a separate lane for only HOV vehicles to use for approximately 1 hour a day, 5 days a week. HOVs represent approximately 15 to 20 percent of the total number of vehicles that use a particular ramp. On a 2-lane ramp, HOVs occupy 50 percent of the lanes available, and on a 3-lane ramp, they occupy 33 percent.
5. There is a trade-off between tightening the metering rates to increase the carpool incentive,

and speeding them up to prevent backup on the local streets.

Impacts of the HOV bypass lanes are not limited to their effects on automobile occupancy. These impacts on other aspects of the ramp meter project and on traffic in general, are widespread and important. They are significant enough that they too should be considered before the decision is made to provide for the multiple-occupant vehicle.

CONCLUSIONS

The concept of providing preferential treatment for HOVs on metered freeway on-ramps is being tested for the first time in northern California. During the time frame of this study, the metering rates were set to accommodate existing demand so that the delay at ramp entrances in the queue was generally nominal. The time savings was intended to induce use of carpools, vanpools, and buses with consequent benefits to air quality and energy conservation. Because the delay was nominal, so was the time savings for carpoolers. The changes in automobile occupancy rates were very small, and although they were considered to be real changes, they could not be wholly attributed to the bypass lane incentive, according to this research. Further, some of these changes were probably a result of a shift in route of existing carpools rather than the formation of new carpools.

Although the intention of the bypass lanes is to increase vehicle occupancy, it was also found that they often interfere with the operation of the metering system. Before providing HOV bypass lanes on all new ramp meter projects several factors should be considered, including length of the metering period, time of delay in the metered lanes, mileage of where freeway on-ramps are to be metered, and cost. When the delay in metered ramps is longer, as a result of congestion or slower metering rates, HOV bypass lanes can be very effective. When the metering period is brief, however, and delay is minimal, the initial ramp meter project should not include bypass lanes. However, the design of the initial project should allow for the potential addition of bypass lanes if the future benefits outweigh the negative aspects. For now, the bypass lane strategy in Sacramento is considered a useful and effective means for visibly supporting and providing preferential treatment to carpools and buses. In the future, if congestion increases on Highway 50 as expected, the time savings incentive will be greater.

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Framework for Transportation System Management Performance Evaluation

ORIKAYE GOGO BROWN-WEST

ABSTRACT

A methodology is developed in this paper for the evaluation of transportation system management (TSM) actions. The evaluation is performed quantitatively in terms of goals achievement. A goal achievement function (F) is defined as the ratio of the amount of deviation of the observed or actual operational condition a, of a transportation management program from the before reference condition b, to the deviation of the assumed or expected goals e, from the same reference condition for each and every set of specified goals. In other words, the effectiveness of a transportation system management action is judged by the discrepancy between the before, after, and expected conditions of the program action. By this method, a third dimension (program goal) is considered in the post-implementation evaluation exercise of a TSM action. The validity of the evaluation model was investigated by examining its sensitivity to the number of observations in the before and after conditions. Through analysis it can be shown that the goals achievement function is applicable where the sample size is large and measurement errors are small. It is, however, sensitive to situations where both the sample size and errors in measurement are small. The technique can be applied to both small- and large-scale transportation management actions.

Evaluation of transportation plans has evolved in the past 20 years from a straightforward benefit-cost approach to a more complex cost-effectiveness analysis. The effectiveness framework expands the traditional analysis to include social and environmental factors, in addition to user costs-benefits. All are keyed to making decisions about the preferred plan to be implemented with regard to costs and implementation priorities.

After a project has been implemented, it is important to know how the project has performed, and whether forecast goals have been achieved. A generally accepted method of evaluating traffic management actions does not exist at present, especially after implementation. This is in part because of the difficulty of systematically assessing impacts for a wide range of actions--many with small-scale changes; and reflects the emphasis on implementation rather than evaluation. However, when it is done, post-implementation evaluation primarily consists of before and after comparisons.

NEED

Because the literature contains few post-implementation evaluation methodologies, especially for transportation management programs, there is a need to develop a systematic post-program evaluation procedure that is flexible enough to suit the wide range of traffic management actions and that can be efficient in evaluating traffic management program performance.

Prepared in this paper is a goals achievement function (F) methodology that considers post-implementation evaluation in a three-dimensional context: the before reference condition (status quo or what it was without the program), the after reference condition (observed performance), and the forecast condition, or expected goal. The method considers all three to be valid because to neglect one would give an incomplete picture of the evaluation procedure. Besides, because forecasts or policy goals provide a logical base for goal and objective fulfillment analysis, it is essential that the forecast condition be considered in post-implementation evaluations.

THE GOAL ACHIEVEMENT FUNCTION METHODOLOGY (1)

The goal achievement function technique conceptualizes that a traffic management scheme improves the existing transportation system. The improvement, in turn, increases the productivity or the production capabilities of the material inputs; that is, a traffic management program would allow the production of a larger level of output with the same level of input usage. This transportation productivity may be considered increased safety for both pedestrians and motorists, improved traffic flow and system throughput, decreased environmental pollution, and less delay because of congestion, to mention a few.

Figure 1 shows the basic concept of the goal achievement function approach, namely:

1. System variables that are deductively affected by proposed actions and that inductively affect implemented policy (before and after conditions);
2. The changes brought about by implementation of the program (discrepancy); and
3. The behavior of the variables identified in item 1 in relation to the expected or forecast change, making appropriate allowances for the effects of nonprogram factors (achievement level).

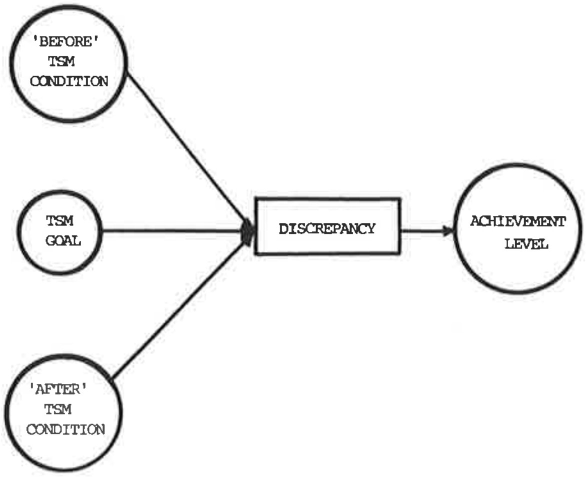

FIGURE 1 **Basic concept of the goal achievement function technique.**

STRUCTURE OF THE GAF TECHNIQUE

Figure 2 represents an overview of the goal achievement function (GAF) approach. Simply stated, the goal achievement function framework provides a means whereby program evaluation focuses on goal-objective achievement rather than on a whole range of effects whose quantification and measurement are often difficult. It identifies the relationships among the evaluation components and planning policies and shows that

1. Traffic management planning studies are carried out in response to certain needs and deficiencies of the existing system;
2. Transportation management actions are then taken to solve perceived problems and to achieve desired goals and objectives;
3. Based on criteria that were established to measure program effectiveness such as reduction in travel time, minimization of accident occurrence, maximization of mobility needs of the population, or minimization of the environmental impacts of transportation, an evaluation of the traffic management program can be carried out;
4. The performance level of the TSM action is then determined by using the goal achievement function F > n, where n is the criterion of measurement arbitrarily chosen by the evaluator to represent an acceptable GAF for the action being evaluated; and
5. On the basis of the resulting evaluation, valuable lessons are drawn from the program's operation, and decisions about its continued operation, modification, or cancellation can be made.

Figure 3 shows the three major components of the goals achievement model, which follow.

1. A TSM production function (J) permits the identification of the underlying trend over a period of time that includes before and after implementation. It assumes a relationship between input and output from the travel production process and determines the discrepancy that has occurred between the before and after measurements in terms of the system variable, that is, the transportation production change as a result of the transportation management action.

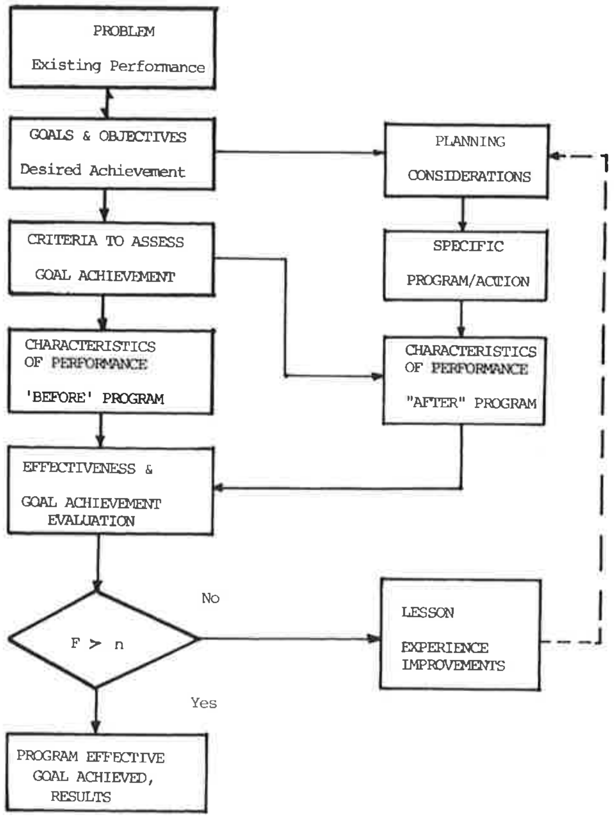

FIGURE 2 **Structure of the goal achievement technique.**

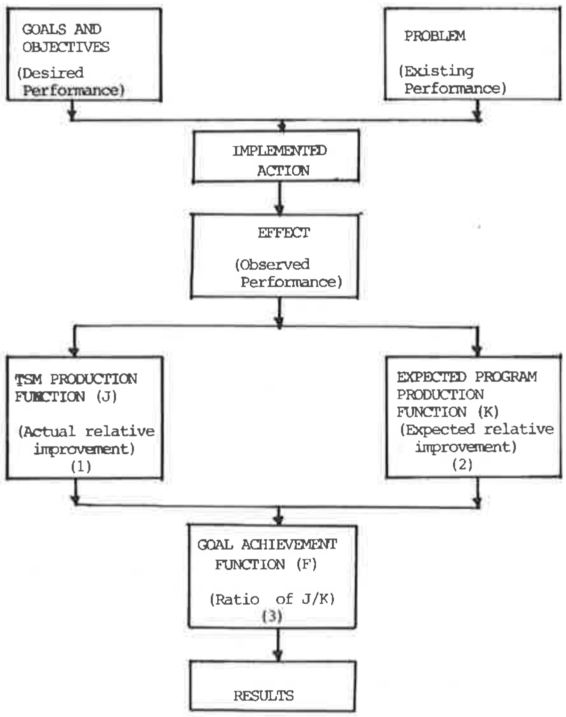

FIGURE 3 **Components of the GAF evaluation model for transportation management actions.**

2. An expected program production function (K) permits the comparison between the expected operational capacity or forecast levels and the before reference condition.
3. A goals achievement function (F) permits the

estimation of program effectiveness on the basis of the net results from items 1 and 2 above. The GAF results from dividing J by K.

By definition a TSM action is expected to improve existing traffic conditions and thereby produce a benefit; and because the differences in the level of performance occur as a result of the action, the production can be related to the action directly.

The transportation system management production function (J) is given by:

$$J = (b - a)/b \tag{1}$$

where b is the activity condition or operational parameter at status quo; and a is the condition after the implementation of the program (TSM production or actual achievement).

By definition, the expected program policy function K, is the transportation production change that occurs between the set or expected goals of a program, e, and the before condition or status quo, b. Expressed mathematically

$$K = (b - e)/b \tag{2}$$

From Equations 1 and 2, a goal achievement function for a given state of a traffic management policy can be derived as follows:

$$F = J/K = (b - a)/(b - e) \tag{3}$$

where a, b, and e are as defined previously.

ASSUMPTIONS

The following assumptions underly the proposed GAF model:

1. The traffic condition repeats itself in a pattern that is susceptible to investigation and quantification;
2. The traffic patterns are predictable because on the basis of item 1, it is possible to reproduce the repetitions;
3. Goals are both rational and realistic. Because management actions are implemented to improve an existing condition, goals will not be set lower or exceedingly higher than is practically achievable;
4. Objectives are defined operationally rather than in abstract terms; that is, objectives can be measured and compared; and
5. The difference in level of performance occurs as a result of the change in the system's operational and physical characteristics (i.e., management action-implemented).

From the preceding, goal achievement has been expressed as the ability of a management action to produce what policy makers expect of it. The question arises as to whether a significant improvement has actually been made as indicated by the measurements and the forecast estimate, and what the magnitude of the total error is in the goal achievement function. In other words, an answer must be provided for the question of how sensitive the function is to its components, as compared with the before condition measurements, b, the after condition measurements, a, and the expected or forecast estimate, e. The sensitivity or validity would depend on

1. Magnitude of error as measured by $S_{\bar{a}}$, $S_{\bar{b}}$, $S_{\bar{e}}$.
2. Sample size used to obtain $S_{\bar{a}}$ and $S_{\bar{b}}$.
3. $S_F = S[(b - a)/(b - e)]$.

And the estimate of F will vary ± $1.96S_F$ with a 95 percent confidence level (assuming a normal distribution). [Note: The assumption of a normal distribution is vital here because sample means are used to obtain the standard error. Furthermore, to evaluate the significance in the difference in means, the normal distribution allows us to assume that they are, in fact, representative of the same population. The general specification for certification of the significance of an observed difference (i.e., the rejection of the assumption that they are the same) is that it must be no more than 5 percent probable and that the difference in means was a result of pure chance is $z = 1.96$.]

S_F can be obtained by using the "propagation of errors" technique. This method asserts that if a quantity Q is a function of n variables, such that

$$Q = f(x_1, x_2, x_3, \ldots, x_n)$$

and each variable of the function is estimated with an independent and random error, $S_{\bar{x}_i}$, such that

$$i = 1, 2, \ldots, n, \text{ where } S_{\bar{x}_i} = S/\sqrt{n - 1}$$

then the total error (Eq) of the value of Q is given by partial differentiation whereby

$$Eq = \left[(\delta Q/\delta x) \cdot S_{\bar{x}_1}\right]^2 + \left[(\delta Q/\delta x) \cdot S_{\bar{x}_2}\right]^2 + \ldots + \left[(\delta Q/\delta x) \cdot S_{\bar{x}_n}\right]^2 \tag{4}$$

In our case,

$$F = (b - a)/(b - e)$$

If $S_{\bar{a}}$, $S_{\bar{b}}$, and $S_{\bar{e}}$ are the standard errors of the mean in a, b, and e, respectively, then

$$\begin{aligned}\left[(\delta F/\delta b) \cdot S_{\bar{b}}\right]^2 &= \left[\left\{(b - e) - (b - a)/(b - e)^2\right\} \cdot S\right]^2 \\ &= \left[(a - e)/(b - e)^2 \cdot S\right]^2\end{aligned} \tag{5}$$

$$\left[(\delta F/\delta e) \cdot S_{\bar{e}}\right]^2 = [\{(b - a)/(b - e)^2 \cdot S]^2 \tag{6}$$

$$\left[(\delta F/\delta a) \cdot S_{\bar{a}}\right]^2 = \left[1/(b - e) \cdot S\right]^2 \tag{7}$$

And the total standard error S is

$$S_F = [1/(b - e)^2]\ [S_{\bar{b}}^2\,(a - e)^2 + (b - e)^2 S_{\bar{a}}^2 + (b - a)^2 S_{\bar{e}}^2]^{1/2} \tag{8}$$

APPLICABILITY AND IMPLICATIONS

The model approach that has been proposed is basically heuristic in nature, a sketch planning-type technique that can be used to assess program performance especially in practically data-deficient environments. It also allows for flexibility on the part of the user to examine effects for a variety of measures. However, it should be applied carefully.

AN EXAMPLE

A traffic management plan was expected to reduce traffic volume within the city center (CBD) from 40,000 vehicles to 20,000 vehicles. After the action, it was observed that the number of vehicles that entered the CBD was actually 30,000. On the basis of established traffic-counting practice, it was assumed that the before volume count had a standard error of the mean ($S_{\bar{b}}$) of ± 600, the after count had a standard error $(S_{\bar{a}})$ of ± 400, and the forecast was estimated to have a standard error $(S_{\bar{e}})$ of ± 300 (assumed); n_b, n_e, and n_a are the corresponding number of observations or counts.

The computation of the goal achievement function of the traffic is as follows:

Given

$$\begin{array}{lll} b = 40{,}000 & S_{\bar{b}} = 600 & n_b = 45 \\ e = 20{,}000 & S_{\bar{e}} = 300 & n_e = 1 \\ a = 30{,}000 & S_{\bar{a}} = 400 & n_a = 45 \end{array}$$

By definition

$$F = (40{,}000 - 30{,}000)/(40{,}000 - 20{,}000) = 0.5 \tag{9}$$

By using the general form for the error in F, the performance level of the TSM action can be computed as follows:

$$\begin{aligned} S_F &= (1/4 \cdot 10^8)\,(4 \cdot 10^8 \cdot 16 \cdot 10^4 + 10^8 \cdot 9 \cdot 10^4 + 10^8 \cdot 36 \cdot 10^4)^{1/2} \\ &= (1/4 \cdot 10^8)\,(64 \cdot 10^{12} + 9 \cdot 10^{12} + 36 \cdot 10^{12})^{1/2} \\ &= (1/4 \cdot 10^8)\,(109 \cdot 10^{12})^{1/2} \\ &= 10.44 \cdot 10^6/4 \cdot 10^8 = 0.026 \end{aligned} \tag{10}$$

But the GAF computation produced

$$F = 40{,}000 - 30{,}000/40{,}000 - 20{,}000 = 0.5$$

Therefore, the range of F for a 95 percent confidence level would be 0.45 to 0.55, based on F = 0.5 ± (1.96) x 0.026.

Now, suppose a, b, and e remain the same but the standard errors have values as shown in Table 1. The standard error (S = 4,000) for the expected condition in this case is a more realistic assumption because the goal is based on a single estimate.

$$\begin{aligned} S &= (1/4 \cdot 10^8)\,(4 \cdot 10^8 \cdot 64 \cdot 10^4 + 10^8 \cdot 16 \cdot 10^6 + 10^8 \cdot 144 \cdot 10^4)^{1/2} \\ &= (1/4 \cdot 10^8\,(256 \cdot 10^{12} + 1600 \cdot 10^{12} + 144 \cdot 10^{12})^{1/2} \\ &= (1/4 \cdot 10^8)\,(2000 \cdot 10^{12})^{1/2} \\ &= 44.72 \cdot 10^6/4 \cdot 10^8 = 0.4472 \cdot 10^8/4 \cdot 10^8 = 0.112 \end{aligned} \tag{11}$$

F = 0.5 ± (1.96) x 0.112, which ranges between 0.28 and 0.72 for a 95 percent confidence level.

Further analysis shows that the goal achievement function is applicable where the sample size is large and errors are small. It is, however, sensitive to situations where both sample size and the standard error of measurements are small. Because of the sensitivity to measurement errors in the values of b, caution should be exercised in its use for actions where the values of b and a cannot be reliably measured (i.e., large standard error of the mean). In other words, if the variances in the values of b and a are large in relation to (b - e), this technique is not an appropriate tool. These observations reinforce the assumptions articulated earlier in modeling the goal achievement function; that measurements be reliable and goals be realistic. Under such conditions the goal achievement technique can be an efficient evaluation tool. Nonetheless, the technique can be applied to both small- and large-scale management actions.

TABLE 1 Standard Error Values

Reference Condition	Volume	Estimated Coefficient of Variation (%)	Standard Error of Volume	Assumed No. of Days Counted	Standard Error of Mean $[S/(n-1)^{1/2}]$
Before	40,000	±10	4,000	11	1,200
Expected	20,000	±20	4,000	1	4,000
After	30,000	±10	3,000	11	800

The method has one additional limitation that underscores the need for careful and selective application. It does not sufficiently account for any systematic error or bias within the measured effects. For instance, it assumes that any discrepancy between the observed and before conditions or any deviation from the expected value can be completely attributable to the management action. This limitation is, however, not critical because historical data are used to establish both the before condition and anticipated effect, and so the effects of annual or seasonal variations are assumed to be marginally accounted for within the data.

PROGRAM COST: A DISCUSSION

Transportation System Management actions and programs are by definition noncapital intensive and relatively inexpensive. Most are, by design, operated and administered within an existing public functionary or body and so do not have direct operational costs charged to them. Second, although the costs of operation and enforcement are considered at the planning phase, design details and operational requirements on implementation have often dictated the development and implementation of low-cost, self-enforcing or partly police-enforcing strategies. Furthermore, a few TSM programs have been known to be included in long-range transportation programs, which presents the problem of when these short-term TSM elements and their corresponding costs must be isolated to provide an efficient performance evaluation.

However, this is not to say that costs are not incurred in one way or another. The exclusion of costs in the goal achievement function approach recognizes that (a) compared to capital intensive and long-range transportation measures, TSM program costs are insignificant; (b) methods already exist that can better evaluate TSM programs involving costs; and (c) the proposed methodology is not a planning tool that makes a choice between alternatives, but is, rather, a means by which actions that are already in place can be assessed.

CONCLUSION

An approach to traffic management evaluation has been proposed in this paper. The goals achievement function--a post-implementation evaluation method--is a comparative process that relates the performance of an implemented project to expected performance or as it would have been if the project were not implemented. It measures the performance or goal achievement of a traffic management strategy.

The technique provides a third dimension to post-implementation evaluation by introducing program goals into it. These goals are important in plan formulation but are left out of plan performance evaluation. By this method, therefore, actual performance is not only compared with the before condition but is also compared with the expected or forecast performance.

In addition, it does not require the transformation of all effects and impacts of the traffic management scheme into monetary terms. Thus, market and nonmarket values can be considered whether or not they are priceable or measureable. This quality is important for making technical and political decisions because it is not possible to transform all outputs and effects of transportation management actions into a single monetary scale. Also, the method allows for subjective analysis in situations where an explanation is required for the observed behavior.

RECOMMENDATIONS

The application of the goals achievement function methodology to actual cases of TSM implementation is recommended as this will further increase program experience, provide valuable insights into transportation decision making and official accountability, and overcome existing obstacles and biases that sometimes inhibit program evaluation.

Also, with the proliferation of transportation system management actions in many cities in recent years and improvements in recordkeeping and data collection methods, there currently exists the data base for more comprehensive modeling. In this regard, it will be necessary to expand the goals achievement function model to include not only program costs but also growth patterns in economic and business activities and trends in social and other behavioral areas within the program environment. Two outcomes: a TSM production predictive model that includes a cost function or a TSM production model, or both, that can be used to evaluate performance of an improved transportation system supply relative to a predetermined cost, and socioeconomic impacts can be appropriate additions to the literature.

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Managing Traffic in Residential Areas

HOWARD McCANN, LARRY TROXELL, and GEORGE KING

ABSTRACT

This report presents traffic management concepts that were developed as part of a traffic plan for the city of Greenwood Village, a suburb of Denver. Greenwood Village includes established neighborhoods in addition to extensive commercial development in the Interstate 25 corridor. The community wishes to preserve its environmental quality while accommodating the traffic demands of commercial development and residential growth. Through travel demand modeling, it was demonstrated that substantial roadway improvements would be necessary to resolve the area's traffic problems. The magnitude of these improvements was environmentally unacceptable. As the forecasted demand exceeded the system capacity, a primary concern was the spillover effect of arterial traffic onto residential streets. This led to the development of a traffic management strategy, which considered the legal aspects of traffic diversion. The recommended plan attempts to manage systemwide traffic by encouraging traffic on selected streets and discouraging it on others. These objectives were accomplished by controlling roadway capacity through allocations of green time at signalized intersections, roadway design features, and travel time penalties. The plan does not totally satisfy the travel demand, but does provide reasonable travel routes for through traffic while minimizing the traffic impact on residential areas.

Greenwood Village is located in Arapahoe County in the southeastern section of the Denver metropolitan area. Initially incorporated in 1950, the community has placed great emphasis on maintaining a high environmental quality.

Greenwood Village also contains an area of extensive commercial development that includes both the Denver Technological Center (DTC) and Greenwood Plaza. Significant development has occurred, and the area is recognized as a primary activity center by the Denver Regional Council of Governments.

A current issue is the extent of future development, and the potential impact of this development on transportation systems and the environment. The DTC occupies approximately 3 million ft^2 of the approximately 11 million ft^2 of planned development authorized by Greenwood Village. Greenwood Plaza similarly occupies approximately 3 million ft^2 with a 7-million ft^2 potential.

TRAVEL DEMAND EVALUATION

Traffic impacts were assessed through the use of a computerized travel demand forecasting model. The first task in the development of a workable model for the study area was to define an acceptable population and employment data base that was compatible with regional growth estimates and local development plans. The data base was in the form of a regionwide trip table.

It was recognized early in the modeling efforts that extensive roadway improvements would be necessary to accommodate the full travel demand. The magnitude of these improvements was deemed to be environmentally unacceptable to the community. An effort was then made to develop a balanced system that would minimize the overall delay on the network.

After multiple tests and system refinements, a test network system began to emerge that would minimize the overall delay. Each successive network and its particular set of link changes resulted in a variation of the overall operating characteristics of the system. The overall efficiency of the system was evaluated in terms of three parameters: (a) free-flowing links, (b) links with conditions between free-flow and capacity, and (c) over-capacity links. The final test network resulted in the best combination of these parameters with an increase in free-flowing links together with a reduction in over-capacity links. In other words, more traffic was operating at or near desired speeds and more roads were experiencing at or below capacity conditions.

The final tests of this network showed that some problems remained. These could not be remedied through further system changes without degrading the environment. The issue became one of evaluating heavy travel demand within an environmentally sensitive area, and led to an investigation of traffic management strategies. Because the forecasted travel demand was greater than the roadway system capacity, a prime concern was the restraint of through traffic in residential neighborhoods.

METHODS FOR MANAGING TRAFFIC

Traffic problems in neighborhoods may frequently be attributed to the spillover effect of congestion on nearby arterials. In recent years this situation has led to the application of various methods, which are summarized later in this paper, of restricting nonlocal traffic. These restrictions take the form of passive or physical controls.

Passive controls include stop signs, speed limit signs, turn prohibition signs, one-way streets, and entry prohibition signs. Speed limit signs are effective when they represent reasonable speeds for certain road conditions. (This limit is generally considered to be the 85th percentile speed of motorists who use the road.)

Physical controls include speed bumps, speed undulations, median barriers, cul-de-sacs, and diagonal diverters. Each prohibits a specific action, and is used to reduce either the speed or volume of traffic flow. However, there are disadvantages associated with this type of control, such as impeded access for local residents and emergency vehicles (police, fire, and medical).

Speed bumps are usually no higher than 5 in., and less than 3 ft in length. They are typically used only on private drives because serious questions exist with regard to their impact on motorist safety. Speed undulations were perfected in England (1), and are a relatively new development. They offer a gradual roadway change, and are 4 in. in height at the midpoint of a 12-ft section. Studies show that undulations produce driver discomfort at speeds greater than 25 miles per hour (mph), and that properly spaced undulations are effective in controlling both speed and volume.

Recent studies by Clement (2) indicate that parabolic-shaped 3-in. high undulations at the midpoint of a 12-ft section are most effective in controlling speeds. The 3-in. high undulations should be spaced approximately 300 ft apart. This spacing will result in vehicle speeds of about 27 mph between undulations, and 23 to 25 mph at the undulations. Clement also pointed out that vehicles with a longer wheel base, such as fire trucks, would operate better if the undulation was at the midpoint of a 16- to 20-ft section.

Passive or physical controls are best applied as part of an areawide solution. Without the areawide plan, traffic problems may be shifted from one location to another. Strategies may be developed for perimeter control to prevent vehicles from entering a residential area, or for internal control at isolated locations.

The concept of environmental capacity, as developed by Marks (3), was applicable in determining the need for traffic management in Greenwood Village. Environmental capacity was defined as "the volume and character of traffic permissible on a particular street consistent with the maintenance of good environmental conditions." Environmental capacity (vehicles per hour) is a function of pedestrian delay, noise, fumes, vibration, and visual distraction. An examination of current traffic volumes reveals that the environmental capacity is currently exceeded on many streets in Greenwood Village. The recommended plan should minimize traffic impacts in residential areas to the maximum extent possible.

LEGAL CONSIDERATIONS

A study by Van Antwerp (4) showed that challenges to traffic diversion strategies may fall into four general groups:

1. The power of municipalities to manage traffic,
2. The reasonable exercise of such power,
3. Consequences of denial of access for through-traffic motorists and local residents, and
4. Compliance of diversion strategies with state or federal codes with regard to uniform traffic control devices.

The first and second issues have been addressed in several U.S. Supreme Court cases. The Court has upheld zoning legislation, which has similar objectives to traffic diversion. In the zoning case of the Village of Euclid versus the Ambler Realty Company (272 U.S. 365), the Court cited that zoning will "tend to prevent street accidents . . . by reducing the traffic and resulting confusion in residential sections." The Court believed that the absence of zoning would lead to problems "until finally, the residential character of the neighborhood and its desirability as a place of detached residences are utterly destroyed."

Similar conclusions were reached in Village of Belle Terre versus Boraas (416 U.S. 1). The Court cited that

> a quiet place where yards are wide, people few, and motor vehicles restricted are legitimate guidelines in a land use project addressed to family needs . . . . The police power is . . . ample to lay out areas where family values, youth values, and the blessing of quiet seclusion and clear air make the area a sanctuary for people.

In a similar case, the County Board of Arlington County, Virginia versus Rudolph A. Richards (434 U.S. 5), the Court cited that

> A community may decide that restrictions on the flow of outside traffic into particular residential areas would enhance the quality of life thereby reducing noise, traffic hazards and litter . . . . The Constitution does not outlaw these social and environmental objectives . . . .

From a review of court cases, it appears that the exercise of police power, through land use zoning or traffic restriction, is valid if it has a substantial relation to public health, safety, and general public welfare, and is neither arbitrary nor unreasonable. Other legal considerations involve the rights of access of both through-traffic motorists and residents. Van Antwerp (4) cited that no compensable damage had been done unless residents were denied total access to their property. For through-traffic motorists, courts were similarly unwilling to give credence to complaints as long as alternate travel routes were available.

Some questions have arisen, however, with regard to the validity of diversion methodologies because some are not specified in the Uniform Manual of Traffic Control Devices (5) or in applicable state traffic codes. This issue was the basis for the case of Rumford versus the city of Berkeley [31 Cal. 3d 545, 645, p.2d. 183 Cal. Rptr. 73 (1982)], in which the legality of traffic diverters was questioned. The California courts held that the diverters were illegal because they did not conform to the specifications for official traffic control devices in the California Vehicle Code.

This ruling resulted in a new legislative act to redefine the meaning of "official traffic control devices," and excluded "islands, curbs, traffic barriers, or other roadway design features" from this category. This new legislative act also gave local governments the authority to adopt regulations that prohibit "entry to, or exit from, or both, from any street by means of islands, curbs, traffic barriers, or other roadway design features to implement the circulation element of a general plan. . . . ." The act further stated that "the regulations . . . shall be consistent with the responsibility of local government to provide for the health and safety of its citizens." The provisions of access for emergency vehicles was apparently a consideration in the "health and safety" clause.

On the basis of the review of legal issues and previous research, the following steps are recommended in developing a traffic management strategy:

1. Perform a comprehensive traffic study, and develop a full understanding of the problem.
2. Consider the inconvenience caused to both residents and through-traffic motorists. Viable alternative routes should be provided for through-traffic motorists.
3. Consider emergency vehicle (police, fire, ambulance) movement.
4. Consider the movement of trucks, and provide specific truck routes.
5. Involve both residents and local officials in the planning process.
6. Develop a traffic management plan as part of the areawide traffic circulation element of a general plan.
7. Gradually implement the traffic management plan to provide both residents and through-traffic motorists with an adequate adjustment period.
8. Monitor traffic flow at appropriate locations to assure that the plan objectives are accomplished.

TRAFFIC MANAGEMENT CONCEPTUAL PROGRAM

The recommended plan consists of a traffic management program and recommended improvements to both intersections and the road network. The plan attempts to "manage" systemwide traffic flow by encouraging traffic on selected streets and discouraging it on others. Figure 1 shows the traffic management program for a portion of Greenwood Village. Greenwood Village is located between Belleview Avenue and Orchard Road.

For the portion of Greenwood Village that is shown in Figure 1, residential areas are generally located west of Quebec Street and the commercial areas are located east of Quebec Street (Note: Many internal residential streets are not shown in Figure 1.)

The traffic management program was based on a thorough review of the travel demand, as well as the legal constraints to traffic direction. The provision of viable routes for through traffic was a major consideration. The following example illustrates this concept.

As shown in Figure 1, traffic flow is discouraged in the residential areas west of Quebec Street. These areas are impacted by two primary east-west routes, Orchard Road and Belleview Avenue. If both routes were upgraded to accommodate through traffic, the residential areas would be heavily affected. Conversely, if through traffic was restricted on both routes, Greenwood Village would be providing no viable east-west route to accommodate the travel demand. Based on legal considerations reviewed previously, serious questions could be raised about the reasonableness and validity of such an action by Greenwood Village. Thus, the plan encourages east-west movement on Belleview Avenue and generally discourages east-west movement on Orchard Road. This action attempts to balance the need for environmental protection against the need for through-traffic routes for east-west travel demand.

A list of the principal conceptual elements of this plan follows.

1. Traffic flow would be discouraged in the environmentally sensitive residential areas.

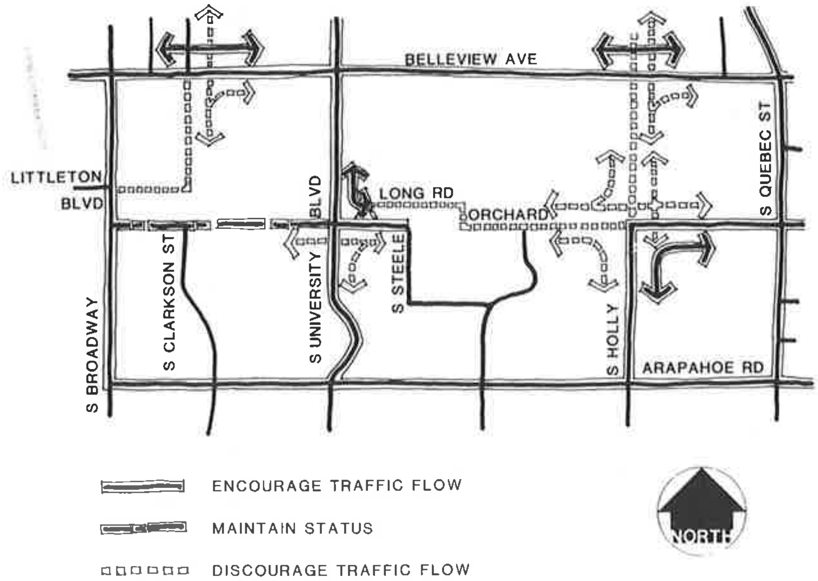

FIGURE 1 Conceptual plan for traffic management in Greenwood Village.

2. Traffic flow would be encouraged in the commercial zone that is located east of Quebec Street.

3. Through traffic peripheral east-west movement would be encouraged on that portion of Belleview Avenue that is adjacent to and west of the commercial area, and on Orchard Road east of Holly Street. East-west movement would be discouraged on Belleview Avenue east of the commercial area and on Orchard Road west of Holly Street.

4. For the portion of the plan shown in Figure 1, through traffic north-south movement would be encouraged on Broadway, University Boulevard, and Quebec Street. Through-traffic movement is discouraged on Littleton Boulevard-Clarkson Street and Holly Street north of Orchard Road.

IMPLEMENTATION OF TRAFFIC MANAGEMENT

Traffic management will be implemented in Greenwood Village by traffic signal timing and geometric improvements at intersections, the use of speed undulations, and roadway widths (number of lanes). A description of the various implementation measures follows.

1. Traffic signal timing and geometric control at intersections. Traffic signal timing is generally a function of traffic demand, with green time allocated to accommodate the traffic flow. However, in a management strategy, green time would be allocated to provide capacity for the desired movements, and to restrict capacity for unwanted movements. A key advantage of the traffic signal control system is that access is unrestricted for emergency vehicles (police, fire, ambulance). Signal timing control is recommended for the intersections shown in Figure 1, where specific traffic movements are encouraged or discouraged.

For example, a three-phase signal could be provided for the Holly Street-Orchard Road intersection shown in Figure 2. One phase could provide for south-east movement, the second phase for north-south movement, and the third phase for east-west movement. The initial signal timing would be set to generally accommodate the existing demand. More time would gradually be allocated to the desired south-east movement, with less time allocated for the other phases. The signal timing would be complemented by signs that prohibit right turns on red lights, and by the construction of additional turn lanes for the desired south-east movement. The additional lanes are shown in Figure 2.

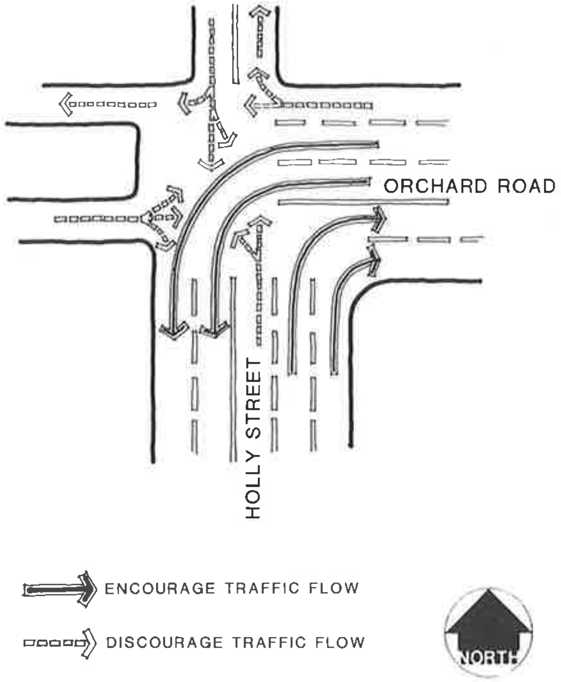

FIGURE 2 Management of traffic flow at an intersection.

2. Speed undulations. Speed undulations may be used to restrict vehicle speeds to 25 mph on selected roadways. Candidates for this geometric roadway treatment would include Orchard Road west of Holly Street, and Holly Street north of Orchard Road.

3. Posted speed limits. As the speed undulations are installed, the posted speed limits should be changed to reflect the goals of the traffic management conceptual program. Thus, the roads with undulations would be signed for lower speeds; conversely, the roads on which traffic flow was encouraged would be signed for higher speeds. Pre-

cise speed limits would depend on the spacing of the undulations (300 ft would reflect a 25 mph speed), and the 85th percentile speed on the other roadways.

4. Unsignalized intersections on arterial roadways. There are several unsignalized intersections on principal arterials that provide access to Greenwood Village residential areas. Residents have occasionally requested signals at these locations. Although the traffic volume does not satisfy signal requirements as specified in the Manual on Uniform Traffic Control Devices (5), motorists are forced to wait for openings in the traffic stream, and experience a poor level of traffic service. However, this poor level of service is also experienced by nonresidents who may wish to drive through the neighborhood. Traffic signals would facilitate turns by both residents and nonresidents.

The present practice of installing left-turn bays at these unsignalized intersections appears to be the appropriate solution. The left-turn bays allow for motorists on the arterials to safely turn; they also facilitate through traffic on these arterial roadways. Residents will experience delays on the unsignalized cross streets, but these delays also discourage nonresidential through traffic during the peak periods.

5. Roadway width (number of through lanes). The roadway plan for Greenwood Village proposes a recommended number of through lanes and complements the recommended traffic flow plan shown in Figure 1. Roadway widening was proposed for several routes, including Belleview Avenue and Quebec Street, on which traffic flow was encouraged. Travel access to the commercial development east of Quebec Street will be enhanced with the proposed roadway improvements to Belleview Avenue, Orchard Road, and Quebec Street. As mentioned previously, these recommended improvements will not totally accommodate the anticipated travel demand, and traffic management measures must be implemented to prevent through traffic from using residential streets.

ACKNOWLEDGMENT

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Traffic Management in Bangkok

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ABSTRACT

Traffic congestion in Bangkok, Thailand, which has a population approaching 6 million, is a daily occurrence that involves many hours of wasted time for the residents, considerable waste of scarce fuel resources, and a deterioration of the environment through air and noise pollution. Although car ownership is relatively low in comparison with western cities, the road space per area is less than one-half that of most other capitals. The city's traffic congestion is being tackled by improvements and priorities to public transport, area traffic control, highway improvements, and law enforcement. The Office of Policy and Planning has been instrumental in reviewing alternative measures of traffic restraint and undertaking improvements to traffic signals. This began with the introduction of a microprocessor area traffic control system for the city center before the introduction of an areawide system. More than 100 km of with-flow bus lanes have been introduced to complement the contra-flow bus lanes, and these now provide the most extensive bus priority system of any city in Southeast Asia. The benefits to the high volumes of buses and minibuses that use these lanes are considerable. This has been complemented by comprehensive route improvement schemes on many of the main roads in the city and an extensive one-way system. Overall improvements to traffic flow have, therefore, been obtained in recent years which, together with the current plans for further major junction improvements and improvements to traffic enforcement and control, have led to the creation of a new traffic management initiative in Bangkok.

For many years traffic congestion has been a way of life in Bangkok, the capital city of Thailand. Despite the enormous cost of this traffic congestion in terms of resources and wasted time to the nation and the Thai people, it is tolerated and the city continues to survive and grow. However, if the level of traffic congestion is allowed to worsen it will undoubtedly have a detrimental effect on the city's development and future prosperity. The traffic congestion in Bangkok is not only severe, but also unpredictable. The same journey may take 30 min on one occasion and 2 hr on the next at a similar time of day and on corresponding weekdays. These conditions exist because much of the road network is operating close to capacity for most of the day (Table 1).

One of the factors that has contributed to this level of service pattern is that Bangkok has one of the lowest percentages of road space per area in the world. Bangkok's road space amounts to approximately 8.9 percent compared with 22 percent in London and 24 percent in New York. Furthermore, a large percentage of the total road space consists of minor dead-end roads, which only adds to the volume of cars on the few existing main roads. Under these conditions, small incidents such as breakdowns, short peaks in traffic flow, accidents, or storms can cause junctions to overload and complete stoppages to occur.

There are more than 700,000 motor vehicles registered in Bangkok, of which about 500,000 are in daily use on the roads. With the estimate of about 5 million people in the metropolitan area alone, there is a ratio of one vehicle being used daily per 10 people is relatively low in comparison to the United Kingdom where the ratio is four vehicles in daily use per 10 people. However, the increase in the volume of motor vehicles for the last 20 years in Bangkok has outpaced the population growth in the metropolitan area. In 1960 there were less than 100,000 vehicles for the 2 million people in Bangkok, whereas in 1970, that volume of motor vehicles had increased to about 300,000 for the city whose population had increased to 3 million. With increased real income each year and the city population continuing to rise, more vehicles will be on the roads and traffic congestion will spread to a wider area. The benefits to be derived from any improvement to the existing traffic congestion are potentially enormous.

The concern of the Royal Government of Thailand to alleviate, or at least contain, the level of traffic congestion has led to a number of studies and implementation measures over the last 10 years. New roads have been and are being constructed, but because of restrictions on the availability of funds and the limited scope for building new roads without widespread property demolition, this approach can

TABLE 1 Average Levels of Service on Typical Bangkok Roads

Level of Service	Description	Number of Hours Between 6:00 a.m. and 6:00 p.m.
A to C	Good travel conditions. Travel speeds declining slowly as traffic increases.	3.0
D	Deteriorating conditions. Travel speeds declining rapidly as traffic approaches road capacity.	3.5
E	Unstable travel conditions. Roads operating at capacity.	4.5
F	Forced flow conditions. Unstable traffic flow with frequent complete stoppages.	1.0

only provide solutions for particular areas. The Expressway, the Middle Ring Road, and Sathorn Bridge all provide relief in those areas but they are not likely to significantly reduce congestion levels throughout the city. It is clear from the experience of countries in other parts of the world that new roads generate new traffic, and any relief is only likely to be of a temporary nature.

Considerable efforts have also been and are being made to determine the feasibility, role, and effect of an appropriate mass public transportation system. However, it will be some years before the system, if appropriate, is realized, and costs are likely to be enormous. It is clear, therefore, that major investment projects in Bangkok will not provide the total answer to containment of the level of traffic congestion, and the Royal Government of Thailand has recognized this for some time.

In early 1978, the Thailand government reached an agreement with the World Bank for a loan to implement short- and medium-term traffic improvement measures and policies in Bangkok up to the mid-1980s. The implementation of the Bangkok Traffic Management Project (BTMP) includes

- Transport planning and policy,
- Area traffic control,
- Public transport measures,
- Route improvement, and
- Enforcement and training.

It was agreed in 1978 that within the Ministry of Interior, Office of Policy and Planning (OPP), a Committee for the Management of Road Traffic (CMRT) was to be provided with a permanent technical secretariat termed the Office of the Committee for the Management of Road Traffic (OCMRT). Thus, the OCMRT became the traffic planning authority for Bangkok, with further responsibility for coordinating transportation planning and policy in all parts of the country. Jamieson, Mackay, and Partners were appointed by the government to advise and assist the OCMRT.

TRANSPORT PLANNING AND POLICY

Traffic congestion can basically be addressed in a combination of ways. By increasing available road capacity, attempts can be made to accommodate existing and projected traffic demands or, alternatively, an attempt can be made to reduce traffic demand to such a level that existing roads can carry the remaining traffic. Road capacity can be increased by improving vehicle and driving standards, by traffic management measures, or by building new roads. Improving vehicle and driving standards and introducing widespread traffic management schemes must form part of the government's policy, but the overall effect on road capacity is likely to be relatively small and it will take years before widespread improvements can be achieved. It is unlikely that these improvements will even keep pace with increasing vehicle ownership and use. New roads are being constructed, but because of restrictions on the availability of funds and the limited scope for building new roads without widespread property demolition, these can only provide solutions for particular areas.

The alternative approach of trying to reduce traffic demands to a manageable level can be achieved either by traffic restraint, actively deterring motorists from using their vehicles, or providing alternative travel methods that may encourage drivers to change mode of their own free will and leave their vehicles unused.

Traffic restraint can produce rapid and significant effects. Although a small increase in the capacity of the road network may only generate new traffic and rapidly be taken up by increasing vehicle ownership and use, a relatively small reduction in traffic levels can produce large improvements in travel conditions. By removing 10 percent of traffic, average travel speeds for remaining traffic may increase by at least 25 percent.

POLICIES

Traffic policies may be considered under the headings (a) parking, (b) staggered working hours, and (c) traffic restraint.

Parking Controls

Parking controls are a policy measure designed to discourage the uneconomic use of low occupancy vehicles. They can specifically discourage long-term commuter parking, encourage short-term business parking, and remove obstruction to moving traffic. There is generally low priority attached to parking controls by the authorities as compared with other traffic problems, and the organizational structure does not exist for a comprehensive parking policy to be implemented. At the present time, only commissioned policemen have enforcement powers and the enforcement of extensive parking controls would employ a large number of officers who have been trained for much wider duties. The Bangkok Metropolitan Authority (BMA) attendants are only able to collect money and have no enforcement powers.

Despite difficulties in achieving a comprehensive parking policy and implementing this on the street, significant progress was achieved in August 1979. On orders from the Traffic Police Division and following consultations with the OCMRT, strict parking and loading prohibitions were introduced for morning and evening peak periods on 39 major roads in Bangkok. Enforcement levels have proved adequate, the public has accepted the scheme, and peak period travel has been greatly assisted. The success of this major parking control measure could lead to a wider application of similar measures within the city and to the eventual development of a comprehensive parking policy.

Staggered Working Hours

Staggered working hours are generally proposed as a method for spreading and reducing peak travel volume, and in Bangkok it was initially believed that this would be particularly advantageous for bus users. A number of surveys were carried out of both general traffic and bus passenger volumes, and these indicated that Bangkok does not, in fact, have the usual exaggerated peak travel pattern.

Traffic Restraint

There are many ways in which vehicle ownership or use can be restrained. For example, vehicle licenses and fuel taxes could be increased to such a level that only a small proportion of the population could afford to use a private vehicle. Or, all parking spaces could be so tightly controlled or highly priced that only a portion of present-day travellers would be able to find parking spaces or be able to afford to pay the charge. These methods can be categorized as rationing, pricing, or indirect.

Consideration has been given to all appropriate methods of restraint, and Table 2 gives an overall evaluation of these methods. In 1980 cordon pricing (1,2), although it can overcome most problems, was ruled out by the government as impractical. By charging for the use of roads, motorists can be made to pay directly for the congestion costs to which they are contributing. Pricing can be applied only to the area where traffic congestion occurs--at the time of day when congestion is at a peak--and to selected vehicle types. For example, by charging private cars, people will be encouraged to use buses, thereby making greater economic use of the available scarce road space. With fewer people using low occupancy vehicles and more people using buses, it may be possible for more people (rather than vehicles) to travel in the previously congested area with traffic restraint than before. Cordon pricing has been shown to be possible in Singapore, and it is a flexible policy. The restraint cordon, charge levels, vehicle types to be charged, and period of operation, can all be adjusted if changes in the traffic situation occur.

As vehicle ownership and population size grow in Bangkok, all the methods of traffic restraint will have to be considered periodically to correctly balance the city's socioeconomic conditions. For a number of years, Bangkok has banned, except for the expressway, 6-wheeled lorries for 4 peak hr per day and 10-wheeled lorries for 10 peak hr per day. These bans significantly reduce urban travel costs and congestion. This form of traffic restraint is clearly practical and publicly acceptable, but continuing debate will be needed before an appropriate scheme can be identified to reduce the city's growing use of cars.

AREA TRAFFIC CONTROL

Significant improvement has been made in the traffic signal system; before 1978 much of the traffic signal equipment, both controllers and displays, was old and outdated. A key feature of the World Bank loan was the early approval of a negotiated contract with Traffic Engineering Systems Ltd. (TESL), in association with the General Electric Company (GEC), Elliott Traffic Automation Ltd., who, over a number of years had supplied virtually all of the existing equipment. This contract was for the supply and installation of a compact, microprocessor-based, Area Traffic Control (ATC) system, together with an extensive network of cableless linked controllers (Figure 1).

The contract was signed in April 1978 for the supply, installation, and maintenance of a GEC "highwayman" ATC system that would control 48 intersections in the old section of the city. The control center is located in the OPP building and is connected by the Telephone Organization of Thailand lines to GEC Type 25 intersection controllers. The system was completed on time and switched on in early May 1979 by the Minister of Interior.

During the first few months of operation, a number of amendments to the fixed time signal plans was needed, as traffic patterns changed under the improved method of control. The system covered the core area of the city, and a number of journey time measurements indicated that there had been an overall improvement of approximately 25 percent. A com-

TABLE 2 An Evaluation of Traffic Restraint Methods (2)

	Can Restraint Be Applied Only to Traffic Causing Congestion?			How Difficult to Implement?				How Difficult to Enforce?		
Issue, Restraint Method	Can Be Restricted to Area of Congestion?	Can Be Restricted to Time of Congestion?	Level of Restraint Can Easily be Adjusted?	Can Be Implemented Quickly?	Requires New Administration?	Requires New Laws?	Would Need Better Bus Service?	Special Enforcement Required?	Fraud Possibilities (other than officer corruption)	Would It Raise Revenue?
Fuel rationing	No	No	Yes	Yes, say 6 months	Yes	Yes, straightforward	Yes, whole of Bangkok	Yes, at fuel outlets	Yes, fuel at black-market	No
Odd/even number plate	Yes	Yes	No, only in large increments	Yes, say 6 months	No	Yes, straightforward	Yes, to congested area	Yes, on-street	Yes, duplicate registration plates	No
Car-less day	Difficult	Yes	No, only in large increments	Yes, say 6 months	Yes, but may be part of vehicle registration procedure	Yes, straightforward	Yes, whole of Bangkok	Yes, on-street	Yes, duplicate windscreen licenses	No
Increase fuel/vehicle costs	No	No	Yes	Yes, immediately	No	No	Yes, whole of Bangkok	No	No	Yes
Area road pricing	Yes	Yes	Yes	Yes, say 12 months	Yes	Yes, fairly straightforward	Yes, to congested area	Yes, on-street	Yes, duplicate licenses	Yes
Cordon pricing	Yes	Yes	Yes	Yes, say 12 months	Yes	Yes, fairly straightforward	Yes, to congested area	Yes, on-street	Yes, duplicate licenses	Yes
Parking controls	Yes	Yes	No	No	Yes	Yes, complex	Yes, to congested area	Yes, on-street and on private property	No	Yes
Strict vehicle tests	No	No	No	No	Yes	No	Yes, whole of Bankok	Yes, on-street	No	No

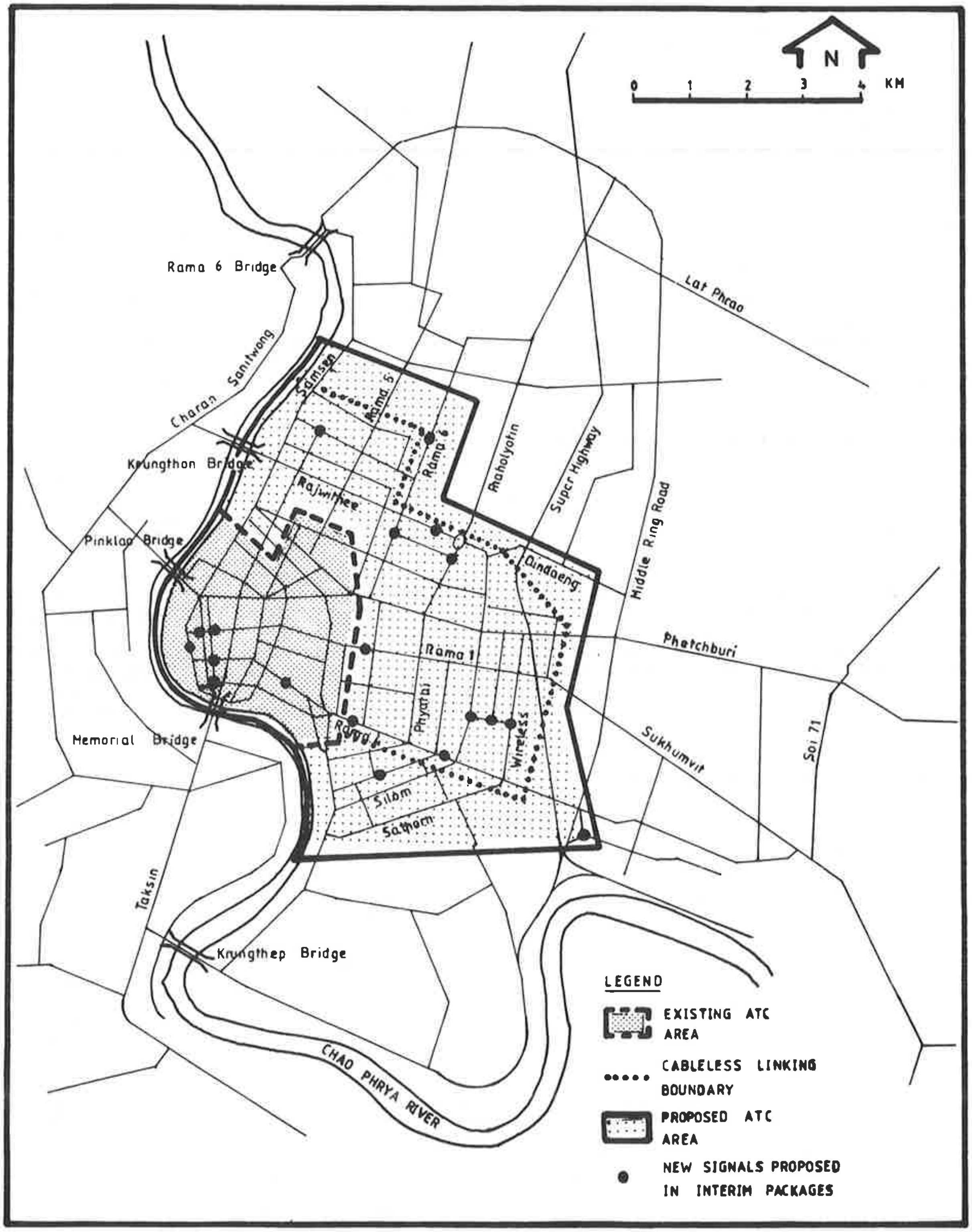

FIGURE 1 Bangkok–area traffic signal control.

prehensive research study was conducted by the Asian Institute of Technology (3) to determine the effects of the ATC system. The study showed that a significant change occurred in the speed of cars before and after the introduction of the system (Table 3). The bus travel times were also substantially reduced. The overall system is estimated to save annual fuel consumption between two and four times its capital cost (4).

A second part of the TESL contract was the supply and installation of 44 GEC Type 25 controllers to create a network of coordinated signals that included the major arterial routes from the north and east areas of the city. The cableless linked system

TABLE 3 ATC System—Changes in System Speed, Cars (3)

Time Period	System Speed (km/hr) Before	After	Change (%)	Number of Road Sections in System
7:00 a.m.-9:00 a.m.	14.9	15.5	4.0	20
9:00 a.m.-4:00 p.m.	12.8	16.6	29.7	25
4:00 p.m.-6:00 p.m.	12.5	17.5	40.0	18
6:00 p.m.-8:00 p.m.	18.7	24.5	31.0	16

Note: System speed is defined as traffic demand (vehicle kms) divided by time spent in the system (vehicle hours), for each time period.

was completed on time and began operating in May 1979. However, traffic police continued to operate the controllers manually for long periods, especially along the heavily congested corridors of Rama 4, Rama 1, Phetchburi, Phayathai, and Rajrarop, and only limited use was made of the system's coordination capability.

In January 1980, systematic testing of part of the area (Rama 1) was begun in an attempt to fully commission the signal network and to demonstrate its capability to police. The signal timings were carefully adjusted to 150-sec cycle time, and the police allowed the system to operate automatically for the "after" survey. Extensive congestion resulted and, after 2 days, the trial was abandoned. A study of the results of this trial indicated that a cycle time longer than 150 sec was likely to prove beneficial, but probably not as beneficial as the 250- to 300-sec cycle times that are currently used by the police over most of the city.

To maintain the program of improvements and modifications of Bangkok signals and to supply urgently required new installations following road improvements by the BMA, additional contracts for installations have been awarded by local competitive bidding to two other international traffic signal companies, thus broadening the range of products available. The success of the central ATC has illustrated the potential benefits to be gained by the enhancement of the system to provide control over a city-wide area. Bangkok currently has approximately 230 signal installations and this number is expected to reach 300 in the near future. In the 10-yr lifetime of an ATC system, this number could easily rise to 500.

Specifications and contract documents were completed in mid-1984 for a modern area traffic control system that covers all signal installations within the Bangkok metropolitan area. The system will be based on the use of fixed time plans. Traffic-responsive systems are not appropriate because of (a) the large number and high level of maintenance required for the detectors, and (b) the consistently high volumes of daily traffic.

All signal controllers in Bangkok will either be replaced or modified to provide down-line loading of plans, timetables, and system time. All signal heads and cables will be refurbished or replaced to ensure that each junction is consistently equipped to the highest modern standards. Because down-line loading is incorporated, a dual computer system is not considered necessary, but a separate Traffic Engineering Computer System to run TRANSYT and various off-line traffic engineering software has been specified. The system will also include some 50 flow-occupancy detectors and a 15-camera closed-circuit television system.

The prequalification of suppliers was completed in late 1983, and it is anticipated that implementation of this system will commence in early 1985, after having been procured through international competitive bidding. The initial city center ATC scheme proved to be the nucleus about which area traffic control expertise could be developed, and now a comprehensive system with adequate power is about to be implemented.

BUS PRIORITIES

Bangkok now has the most extensive system of bus lanes of any city in Southeast Asia (5). Although the city has had contra-flow bus lanes in operation for some years, it was not until April 1979 that the traffic law was modified to enable the practical implementation of with-flow bus lanes, for which signing and road-marking standards were approved in April 1980. During 1979 and early 1980, great emphasis at the administrative level was placed on the conservation of energy in order to reduce fuel consumption for buses.

The government directed the OPP to implement extensive bus lanes. The OCMRT carried out the design and supervision of implementation of approximately 100 km of peak-period with-flow bus lanes on major streets in Bangkok in May 1980. The period between the government directive and the date of enforcement of the measures was only 3 weeks. The routes are shown in Figure 2.

The bus lanes have a number of unusual features and their implementation was specially studied by the Asian Institute of Technology and the Transport and Road Research Laboratory (TRRL). (See Table 4.) One uncommon feature of the Bangkok bus lanes is their length and extent. They operate on most of the major radial roads and on several cross routes and city center streets; for example, the bus lane on Sukhumvit Road is about 12 km long. The bus lanes essentially provide a reserved track for buses in contrast with bus lanes elsewhere that are shorter and are commonly a method of simply jumping localized traffic queues. Bus flows in the bus lanes are very high with nearly 200 buses per hour in Charoen Krung and 250 buses per hour on Phaholyothin Road, which rises to nearly 300 buses per hour and 400 buses per hour, respectively, when minibuses are included. In double bus lanes, over 450 buses per hour are normal. All buses operate on scheduled stopping services.

Although bus flows remained high, their stop times were very short (about 13 sec) and, where problems occurred, elements of comprehensive route improvement schemes were introduced, such as bus bays, central islands, junction improvements, and so forth. The law and road markings permit traffic to and from sois (local streets) to cross bus lanes at right angles. Although there is some danger in the maneuvers, the procedure has been proved to be workable, and only minor supervision is required by the police during peak periods.

Minibus operators were given the opportunity to register with the Bangkok Mass Transit Authority (BMTA) and thus, to legally use the bus lane facilities. Approximately 70 percent of the operators took advantage of this opportunity. The minibuses in the city contribute a significant amount to public transport, as occurs elsewhere in Southeast Asia. Travel time by car and bus was reduced after the introduction of the bus lanes. The initial bus-lane regulations did not permit buses to leave lanes, but these regulations were subsequently relaxed without significant loss of journey speed, although nearly one-half of the buses were running outside the bus lanes.

In February 1984, a major one-way traffic flow system was introduced in the congested central area of the city. As part of this system, an extensive

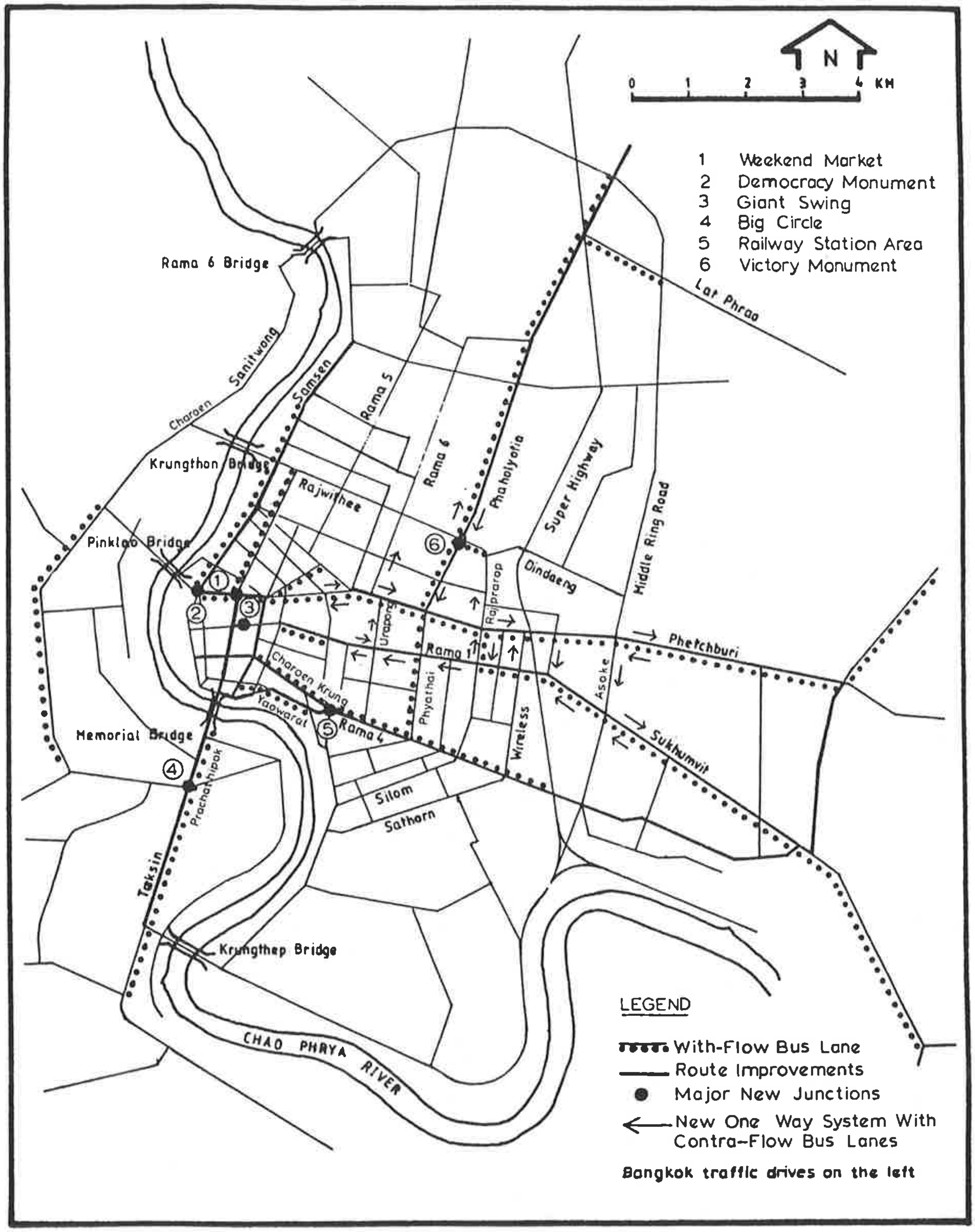

FIGURE 2 Bangkok—traffic management schemes.

network of contra-flow bus lanes was introduced to enable buses to maintain their routes. In addition, the implementation of with-flow bus lanes early in the project resulted in a gain of considerable experience in design, operation, and enforcement measures for bus priority schemes. This is now being applied effectively to contra-flow bus lanes as well. Bangkok, therefore, can now boast of having one of the largest bus priority networks in the world and can provide guidance for other areas of the world in terms of bus operations, enforcement, and capacities.

ROUTE IMPROVEMENTS

In the late 1970s, the standards of traffic management facilities such as street signing, marking, and

TABLE 4 Bus Travel Times Before and After Installation of With-Flow Bus Lanes *(6)*

Bus Lane Section	Length (km)	Mean Travel Time (min)				Mean Speed (km/hr)	
		Before	After	Difference	Change (%)	Before	After
Sukhumvit Road							
a.m. westbound	4.85	15.33	13.55	−1.78	−12	19.0	21.5
p.m. eastbound	4.85	14.90	14.74	−0.16	−1	19.5	19.7
Phaholyothin Road							
a.m. southbound	2.50	5.36	4.87	−0.49	−9	28.0	30.8
p.m. northbound	2.50	7.45	5.47	−1.98	−27	20.1	27.4
Yaowarat Road							
a.m. westbound	2.13	8.33	8.11	−0.22	−3	15.3	15.8
Charoen Krung							
p.m. eastbound	1.09	6.28	5.81	−0.47	−7	10.4	11.3

so forth, were generally not sufficient to undertake improvements separately and, therefore, a comprehensive approach to route improvements was adopted to improve street capacity and driver behavior and to make traffic regulations as self-enforcing as possible. Comprehensive route improvement schemes were, therefore, designed along main roads to be implemented on a staged basis. They would relieve key points of congestion, improve road safety, and enhance bus operations. Many schemes have now been completed, such as Rama 1, Rama 4, Phayathai, and Prachathipok. Other schemes are ready for implementation and further schemes are under consideration. The completed schemes serve as demonstrations of good traffic management practice and standards, and this type of work will be continued on new and existing roads.

Major junction improvement schemes are also planned at locations where the problems of private vehicles, buses, pedestrians, and the environment interact. The improvement of the Weekend Market area, Democracy Monument, Giant Swing, Big Circle, and the railway station area are now complete.

A major one-way traffic flow system in the central area of Bangkok was introduced by the Metropolitan Police Bureau on an experimental basis in February 1984. The system underwent some modification during the initial period of experimentation and in late February was declared permanent.

The permanent system involves some 25 km of major highway within the area enclosed by Dindaeng-Victory Monument in the north, Rama 1 Road Sukhumvit Road in the south, Soi Asoke in the east and Rama 6-Urapong in the west. The system affects and has required modifications to some 30 major intersections. Most of the intersection modifications that have been undertaken as part of the experiment were of a somewhat temporary nature. Redundant signals have sometimes been left in place, road markings have been temporarily painted out, and channelization adjustments have involved removal but not reinstatement in more appropriate locations. Many problems remain at intersections and along the links. These problems involve safety and capacity impedance for vehicles and pedestrians, such as

1. Pedestrians who cross in safety both at intersections and midlink.
2. Consistent and safe control of intersections.
3. Bus flow within the contra-flow and with-flow bus lanes and the effect of these on safety for other road users.
4. Bus stop operation, capacity, and location, which sometimes affect upstream intersection operation and link capacity.
5. Problems of taxi and samlor (a 3-wheeled motorized vehicle with a driver and 2 or 3 passengers) stopping.
6. Driver confusion in terms of lane use, merging and diverging.
7. Police control and enforcement.

The introduction of the one-way traffic system means that considerable change must be made to improve its efficiency and modify some of the comprehensive route improvements. Nevertheless, the lessons learned in how well traffic management design can improve safety, capacity, and driver behavior have not been forgotten. Route improvements are under design for roads within and without the one-way system. The early schemes provided the training ground for designers, and this experience has enabled them to quickly adapt schemes to accommodate major traffic circulation changes in the city. The route improvement schemes have thus proved to be beneficial, low cost, and most important, amenable to rapid major change.

TRAFFIC LAW ENFORCEMENT

Traffic violations play a significant role in obstructing the traffic flow in Bangkok. The most common offenses are illegal parking, jumping the red traffic light, and illegal use of bus lanes. Drivers in Bangkok are currently fined only if they are stopped by the police immediately after committing an offense. On average, 50,000 tickets for traffic offenses are issued monthly and, on average, 85 percent of the offenders fail to report to the police. In 1979, of those offenders who were processed, less than 1 percent were only cautioned, the remaining 99 percent paid a fine of some type.

Much of the traffic policing effort is spent on manual control of traffic signals but, apart from a relatively small number of key intersections, this practice could be eliminated. The day-to-day control of the intersections could be left to intermittent control by mobile police units. This, of course, would require an increased use of radio-controlled solo motorcycle patrolmen who are well-enough trained in modern traffic-control techniques to be able to take over the signals for short periods of time at peak periods. Such a system of traffic police control must be introduced in stages, starting from a small, selected central area and expanding outwards. It is essential that this system be in operation by the time an expanded system of area traffic control is introduced in 1986 and, accordingly, appropriate training under the project has now begun.

Traffic policing clearly must be coordinated with traffic management and control improvements that have been or will be implemented. The goals of any police traffic department should be to (a) ensure the free flow of traffic, (b) ensure the safe movement of traffic, and (c) enforce the traffic law. These goals cannot be considered in isolation but are interdependent. The objectives of the police training will incorporate all three elements.

The situation in Bangkok is such that the police training program should be accompanied and followed by changes in the organizational and operational structure to obtain the best results. The present organization of the police traffic effort, however, creates two problems: (a) the number of mobile units is very small--there are only between 40 and 50 men on cars and motorcycles at any one time; and (b) the men employed on foot control at junctions are in a separate command structure from the traffic division. Their efforts are only coordinated at the deputy commissioner level at police headquarters. A more logical organization arrangement would be for the commander of the traffic division to have overall responsibility for all traffic policing.

SUMMARY OF PROJECT ACHIEVEMENT

Since its inception in 1978, the BTMP has achieved much. An initial city center area traffic-control scheme, approximately 120 km of bus lane, 25 km of one-way street, 4 route improvement schemes, and 4 major junction improvements are some of its directly visible successes. Its most outstanding achievement by far has been the development of a high level of traffic signal and traffic management design and implementation expertise within the OCMRT. This is now reflected in the ongoing design work for further measures.

Implementation of enhancements to all the previously mentioned pilot projects is now planned during the remainder of the project, and these enhancements will prove effective in containing the level of traffic congestion. It is expected that the roles of the OCMRT (planning), BMA (design-implementation), and the Traffic Police Division (enforcement) will be coordinated and enhanced as a result of continued appropriate training provided to each organization under the project.

The BTMP can be viewed as a successful project of traffic management, control, and training and is demonstrating its flexibility by remaining appropriate to a rapidly growing and changing city over almost a decade.

The expertise of the OCMRT staff is now demonstratively high and that of the BMA staff is being enhanced to meet the imminent requirements for new and wide area ATC system operation. Improvements in traffic police enforcement is now to be emphasized through training under the project.

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Abridgment

Contracting Maintenance for Traffic Signal Systems

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ABSTRACT

Traffic signal system maintenance by contract has become a trend for large and mid-sized metropolitan areas in New York state, particularly where labor is highly unionized. One reason for this trend is that it is often possible to increase the level of maintenance services provided at a comparable cost while avoiding personnel administration problems. Between 1985 and 1986, the New York State Department of Transportation (NYSDOT) will let a contract for the maintenance of the Integrated Motorist Information System (IMIS) on Long Island. Before the contract documents for the IMIS were prepared, however, the NYSDOT studied the policies and practices of other public agencies that currently user traffic signal maintenance contracts. These agencies were the State of Indiana Department of Highways, the Illinois Department of Transportation, the Westchester County Department of Public Works, and the Nassau County Department of Public Works. The Nassau County example serves as a case study for this paper. A brief cost evaluation of the Sunrise Highway contract is presented. It is concluded that there are many applications where contracting maintenance for traffic signal systems is cost-effective. Contracting traffic signal system maintenance will play an increasing role inthe future of New York State.

All traffic signal systems that are operating today have at least one common element: the need for maintenance. Some of the most sophisticated traffic control systems in the United States have progressed from design to construction to operation with only minimal emphasis on planning for and estimation of future 'maintenance requirements. Without proper maintenance, traffic control systems that were justified on the basis of an attractive benefit-cost ratio will increase in cost and decrease in benefits. Over time, this results in a system that falls far short of the original estimation of payback to the general public.

The first step toward proper maintenance of existing traffic signal systems is an inventory of the system hardware. A complete set of "as-built" plans and specifications for the system are a necessity. When contractual maintenance is performed, duplicate sets should be given to the contractor at the outset of the job, and returned when the contract is completed.

In general, traffic signal system maintenance can be classified as remedial, preventive, and modification. Urban traffic control systems have a tendency to increase both the need for maintenance and the awareness of maintenance needs. The increase in maintenance activity results from the sheer increase in the quantity and complexity of equipment needed to control remote sites from a central location by using a computer. The increased awareness of the need for maintenance results from the high degree of monitoring of equipment possible with central computer control. Many systems produce failure reports that list the type and location of equipment that has failed. New aspects of maintenance that arise with some urban traffic control systems (such as the maintenance and repair of a control center and communication subsystem) often require specialized training for existing technicians or the expansion of the technical staff to include specialists in the computer and data communications technologies. In most cases, competent specialists are hard to find and harder to keep on a governmental agency payroll when the need for specialists in private industry is very strong and salaries are high. Some agencies responsible for operating and maintaining traffic control systems today are finding contractual services for maintenance to be a viable alternative to the use of strictly in-house forces.

ADVANTAGES OF CONTRACTED MAINTENANCE

When contract maintenance is properly obtained and administered, the following advantages can be realized:

1. Technical expertise and labor can be available on an as-needed basis;
2. Cost control and accountability of maintenance activities can be assessed on monthly and yearly bases;
3. Knockdowns of traffic signal equipment can be quickly repaired; and
4. Preventive maintenance can be scheduled and performed on a routine basis.

Contractual services for maintenance can solve some of the problems associated with providing preventive and remedial maintenance, and in many cases, can lower maintenance costs with competitive bidding. A maintenance contract is not dissimilar to a service agreement, in which the technical expertise and labor required are always available and only paid for when needed.

A CASE STUDY

In recent years, the New York State Department of Transportation (NYSDOT) has turned to contractual services for maintenance in a very limited capacity; foremost example is the Sunrise Highway on Long Island. In the future, NYSDOT plans to maintain the Integrated Motorist Information System (IMIS) on Long Island with contractual services. Because of the size of this system, both geographically (128 miles of roadways in a 35-mile corridor) and quantitatively (104 intersections, 70 ramp metering stations, 76 changeable message signs, and more than 2,000 vehicle detectors), NYSDOT maintenance forces alone will not be sufficient to provide the level of service that is crucial to the operation and evaluation of the system.

A typical example of the use of contracted services for traffic signal maintenance is that of the Nassau County Department of Public Works in Mineola, New York. Nassau County maintains approximately 1,400 signalized intersections, 229 of which are part of a computerized traffic control system. The first phase of Nassau County's computerized traffic control system was completed in 1974. The original system consisted of 108 intersections on 5 arterials. Expansion of the system to a projected 600 intersections is currently underway as part of a 5-year program. The system has been maintained in excellent working order for more than 10 years. Both signalized intersections on the computerized system and other signals throughout the county are maintained by contract.

Nassau County currently uses a combination of in-house forces and three competitively bid contracts. One of the three contracts is a "requirements" contract used to accomplish new signal installations and other major work that involves construction. In this context, a requirements contract is essentially a "furnish and install" construction contract. Work is performed on a work order basis, with plans prepared by county personnel. The county purchases quantities of controllers, poles, and signal heads and supplies them to the contractor for installation. The contractor supplies all necessary cables, conduits, hardware, and labor.

The two maintenance contracts currently used by Nassau County are a computer and telemetry (communications system) contract, and a traffic signal maintenance contract that covers the remainder of the field equipment. The rationale for separating the computer and data communications system from other types of hardware to be maintained results from the need to obtain specialists for trouble-shooting and maintenance of the more sophisticated technologies involved. The contracts specify in an appendix a list of equipment in each cabinet. The responsibilities of the respective contractors are clearly defined to eliminate overlapping work and the gray area between communications system problems and some controller and cabinet problems.

Nassau County requires a 2-hr response time on the traffic signal maintenande contract. This required response time is enforced by inspectors who check that the ordered work is completed. Also, radio communications can be monitored to track the contractor's activities. Required response times for the computer and telemetry system contract are specified somewhat differently than in the intersection maintenance contract. A 2-hr response is only required if a call is placed to the contractor between 7:00 a.m. and 3:00 p.m. For calls placed to the contractor after 3:00 p.m., the required response is ". . . no later than 7:00 a.m. the next business day . . . ." This difference in philosophy is derived from the nature of the work involved. Although problems with the computer and data communications system cause loss of benefits to the public, they do not create a hazardous situation.

Nassau County contract administrators stress that inspection is the key to level of service and cost control for maintenance contracts. Nassau County maintains an in-house staff of approximately 1 individual for every 100 intersections. Of these approximately 13 technicians, from 3 to 5 may be on the road patrolling the system in vehicles provided by the contractor. The staff develops and issues work orders for the contractor. Nassau County's maintenance contractors are required to repair traffic signal pole and cabinet knockdowns. This work is performed on a time and materials basis. Nassau County has an in-house staff of individuals on 24-hr call that act as inspectors in case time and materials-type work becomes necessary.

Intersection maintenance is paid for on a monthly basis. Payments to the contractor consist of the price bid per intersection month multiplied by the number of intersections the contractor maintains, less any charges accrued as a result of failure to perform on time. At present, all three contracts are 2-yr contracts that cost Nassau County approximately $1.7 million per year. The traffic signal maintenance contract, effective from July 1984 to June 1986 costs $1,070,000 per year. The requirements contract (January 1984 to December 1985) costs $520,000 per year, and the computer and telemetry system contract (February 1984 to January 1986) costs $115,000 per year.

COST EVALUATION

The decision to go from in-house to contractual services for maintenance is seldom based strictly on a cost comparison. The advantages of contracted maintenance are often personnel administration-related. In New York, the decision to use contractual services has typically been based on necessity and practicality, and not strictly cost-effectiveness. The decision to maintain the Sunrise Highway system by contract was based on the fact that the hardware involved was not the standard for state systems and was relatively difficult to maintain. At least two specialists would have to have been hired on the state payroll and specially trained. At the time, this was not possible. Also, replacement parts for the specialized equipment would have had to be added to the state shop. The decision to maintain the IMIS by contract was the result of a cost study in which several alternatives for operations and maintenance were evaluated (1). Contract maintenance was determined to be cost-effective for this system. The Nassau County Department of Public Works has used contract maintenance for more than 20 years to avoid problems with high overhead and personnel turnover. Nassau County is highly unionized, and electronics technicians are able to earn higher wages working for contractors.

The cost-effectiveness of contracting traffic signal maintenance depends on a number of variables about the traffic signal system to be maintained:

1. The number of intersections,
2. The location of the intersections,
3. The geographic density of intersections,
4. The ratio of the amount of central (system) control equipment versus field equipment for the system, and
5. The type and complexity of the hardware.

The number of intersections to be maintained will affect the cost per intersection that can be obtained. With contract maintenance of a traffic signal system, the cost per intersection has a tendency to decrease with the number of intersections. This is because the costs associated with system hardware, such as central computers and central data communications, are typically low quantity, high-priced items that remain fixed within the range of intersections that the central equipment is capable of controlling. Figure 1 shows the projected total

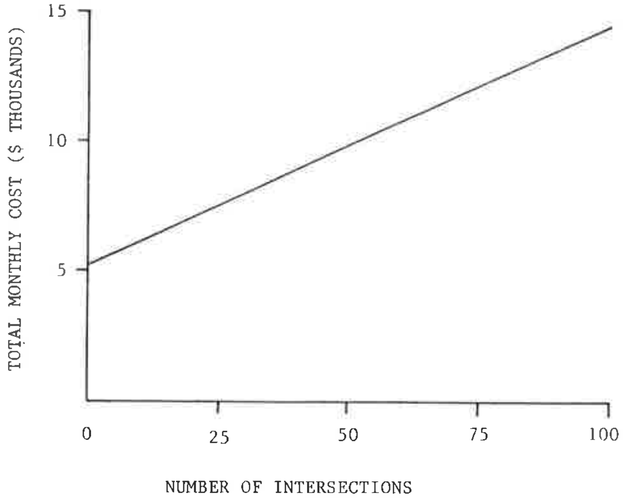

FIGURE 1 Sunrise Highway: projected total contract cost for a range of numbers of intersections.

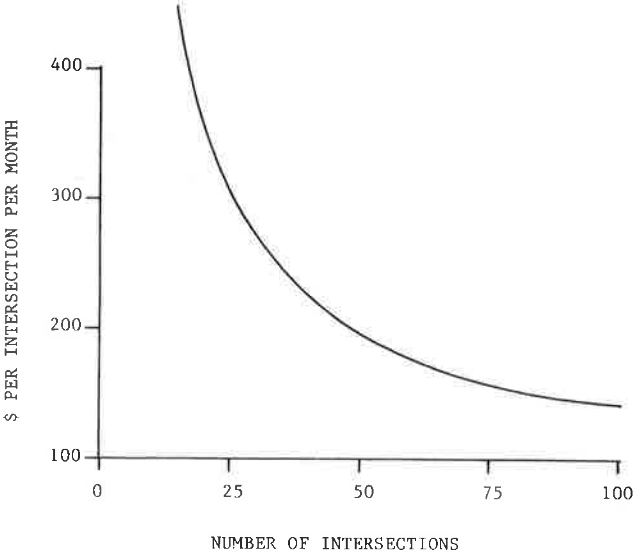

FIGURE 2 Sunrise Highway: projected cost per intersection for a range of numbers of intersections.

cost of the Sunrise Highway maintenance contract for a range of numbers of intersections. The prices used are based on those actually bid for the system with 76 intersections. The items and prices used are given in Table 1. Only the costs related to intersection and detector maintenance increase with the number of intersections, whereas the contract costs that are attributable to master controller stations and other system elements remain stable. Figure 2 shows the total contract cost divided by the number of intersections maintained, or the cost per intersection. As the number of intersections increases, the cost per intersection approaches a minimum of about $90 per month. It is interesting to note that if the cost (based on the Sunrise Highway data) is projected to 1,400 intersections--the size of the Nassau County contract--then the yearly total contract cost would be $1.68 million. The actual Nassau County costs are $1.7 million. This similarity is a result of both contracts being in the same geographic area (signal density, labor, and materials are similar), the same contractor that holds the Sunrise Highway contract also holds two of the three Nassau County contracts, and the specifications used are similar. The hardware involved is very different for the two systems, but the percent of the total contract cost spent on central control versus field equipment is similar. Three of the five variables listed previously are similar.

To compare contract costs with in-house costs, the cost of personnel, materials and supply costs, and overhead should be considered (2). In the highly developed urban and suburban areas of New York, NYSDOT uses a rule of thumb of 1 man per 30 intersections. This is possible because of the geographic density of traffic signals in these areas. In the less dense regions of the state, travel time to some intersections can be as high as 5 hours. The numbers of intersections per crew members in these regions are much lower.

The cost of performing traffic signal maintenance in-house will be sensitive to the same five variables listed previously for contractual services. The savings to be obtained by contracting maintenance result from reducing in-house overhead by taking advantage of the resources that a good electrical construction contractor has available (an electronics repair shop, technical expertise, construction and repair equipment).

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TABLE 1 Sunrise Highway: Contract Bid Items

Item Description	Units	Quantity	Price ($)	Total ($)
Field Items:				
Maintain traffic signal	Per signal	912	60	54,720
Relamp traffic signal	Per signal	76	110	8,360
Detector installation	Per foot	1,000	4.25	4,250
Inductance wire	Per foot	3,500	1.40	4,900
System Items:				
Repair master controller station	Each	2	16,000	32,000
Maintain master controller station	Per station	24	620	14,880
Communication inspection and repair	Lump sum	4	2,200	8,800
Pedestrian Equipment Items:				
Combined	-	-	-	16,650
Construction and Installation Items:				
Combined	-	-	-	22,030
Total				166,590

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Platoon Dispersion over Long Road Links

DAVID E. CASTLE and JOHN W. BONNIVILLE

ABSTRACT

The dispersion of platoons of vehicles as they travel between signalized intersections reduces the potential benefits from coordinating traffic signal timings. The effects of dispersion place a limit on the distance between intersections over which it is beneficial to provide coordination. During a feasibility study for a traffic control system, platoons were observed to remain together for distances up to 2000 m on high-standard arterial roads. Platoon shapes were measured and the results were compared with predictions of the TRANSYT signal timing program by using various values for the TRANSYT platoon dispersion factor. Despite the unusually long distances involved, the most suitable dispersion factor values fell in the same range as those normally used for networks of more typical dimensions. Optimized timings were not found to be unduly sensitive to the dispersion factor used. Requirements to minimize delay throughout the network, and not just on an individual link, act as a constraint on the sensitivity of TRANSYT timings to platoon dispersion rates. On the basis of the observation of platoons on high-standard arterial roads, it was conservatively estimated that coordinated signals could reduce delay by 10 percent, where distances between signals ranged between 1000 and 1500 m.

The dispersion of groups of vehicles as they travel away from a signalized intersection is a familiar characteristic of traffic, created by the differences in speed of travel of the individual vehicles. Models of signalized road networks, including those used within programs to calculate coordinated signal timings, need to account for this phenomenon to provide an accurate representation of vehicle behavior.

The benefits of coordinating neighboring traffic signals are derived through careful timing of the green signals to coincide with the arrival of platoons of traffic from upstream intersections. The longer the distance between intersections, the more dispersed the platoons become and the smaller are the potential benefits from coordination.

Platoon dispersion frequently imposes an upper limit on the distance between intersections over which it is beneficial to provide signal coordination capabilities. This limit is typically between 500 to 1000 m for most road networks. Described in this paper are measurements of the rate of platoon dispersion in a network of arterial roadways of high standard. Through these descriptions, the potential for worthwhile benefits as a result of coordination over distances of 1500 m is demonstrated.

CONTEXT OF STUDY

In many feasibility studies for coordinated signal systems, it is adequate to simply observe, but not directly measure, platoons as they reach the next downstream intersection and base estimates of benefits on results obtained from other cities with similar characteristics. Relevant characteristics include city size, type of network (grid, arterial, or both), sophistication of existing signal equipment (coordinated or not) and average distance between signals.

However, in a feasibility study conducted in the city of Kuwait, the distance between signals was sufficiently long in parts of the roadway network for special studies of platoon dispersion to be undertaken so that the benefits of signal coordination could be estimated. These studies included analysis of platoon dispersion factors to be used in a coordinated signal timing program for this network and an evaluation of the sensitivity of the optimized timings to the value of factor used. This paper contains descriptions of these studies and presents the conclusions reached.

The work was divided into four phases, as follows:

1. Platoon dispersion surveys,
2. Dispersion analysis,
3. Sensitivity of coordinated timings to rate of dispersion, and
4. Estimate of benefits through coordination of signals over long links.

Each phase of the work is described. First, however, it is necessary to briefly describe those characteristics of the Kuwait road system that gave rise to these efforts.

ROAD NETWORK CHARACTERISTICS

Kuwait is the principal city of the country of the same name, situated on the northwest shores of the Arabian Gulf. The country, with a 1980 population of 1.367 million, enjoys a high standard of living as a result of substantial oil reserves. The existing system of roads is the result of many years of careful planning and subsequent execution of these plans. The road system in the urban area of the city is shown in Figure 1.

Within the First Ring Road lies the oldest part of the city, known as Kuwait Town. The central business district (CBD) is contained in this area, and it encompasses large centers of employment, retail activity, and government complexes.

Outside of the First Ring Road, the roads that provide access through the urban area form a network of well-defined radial routes and ring roads. Each of these facilities has been designed and constructed to a high standard. Distances between major intersections along the arterial and ring roads are typically in the range of 1 to 2 km. The radial and ring roads are divided roadways with generally three lanes of travel in each direction. Until recently, all intersections were at grade, in the form of roundabouts, or conventional signal-controlled intersections. Some intersections have now been converted to grade separated, with signalized ramp terminals forming diamond interchanges.

Of equal importance to the high standards of design of the radial and ring roads is the fact that access to the adjacent residential districts is only possible by turning right off the main road at a point midway between intersections (driving is on the right-hand side of the road). Access from the districts is achieved by turning right on the radial or ring roads at a stop sign. This limited access to and from neighboring residential areas gives rise to a comparatively low level of skin friction effects for an urban area, which allows traffic to flow smoothly and rapidly between major intersections.

Other factors also contribute to the smoothness of flow between intersections. First, outside the industrial area to the west of the city, the vehicle mix is dominated by modern passenger cars with comparatively few heavy trucks. Second, the number of public transport vehicles is not large (although it is increasing) and bus lay-bys are provided at all bus stops to minimize the disruption to near-side lane traffic. Pedestrian activity is limited, with

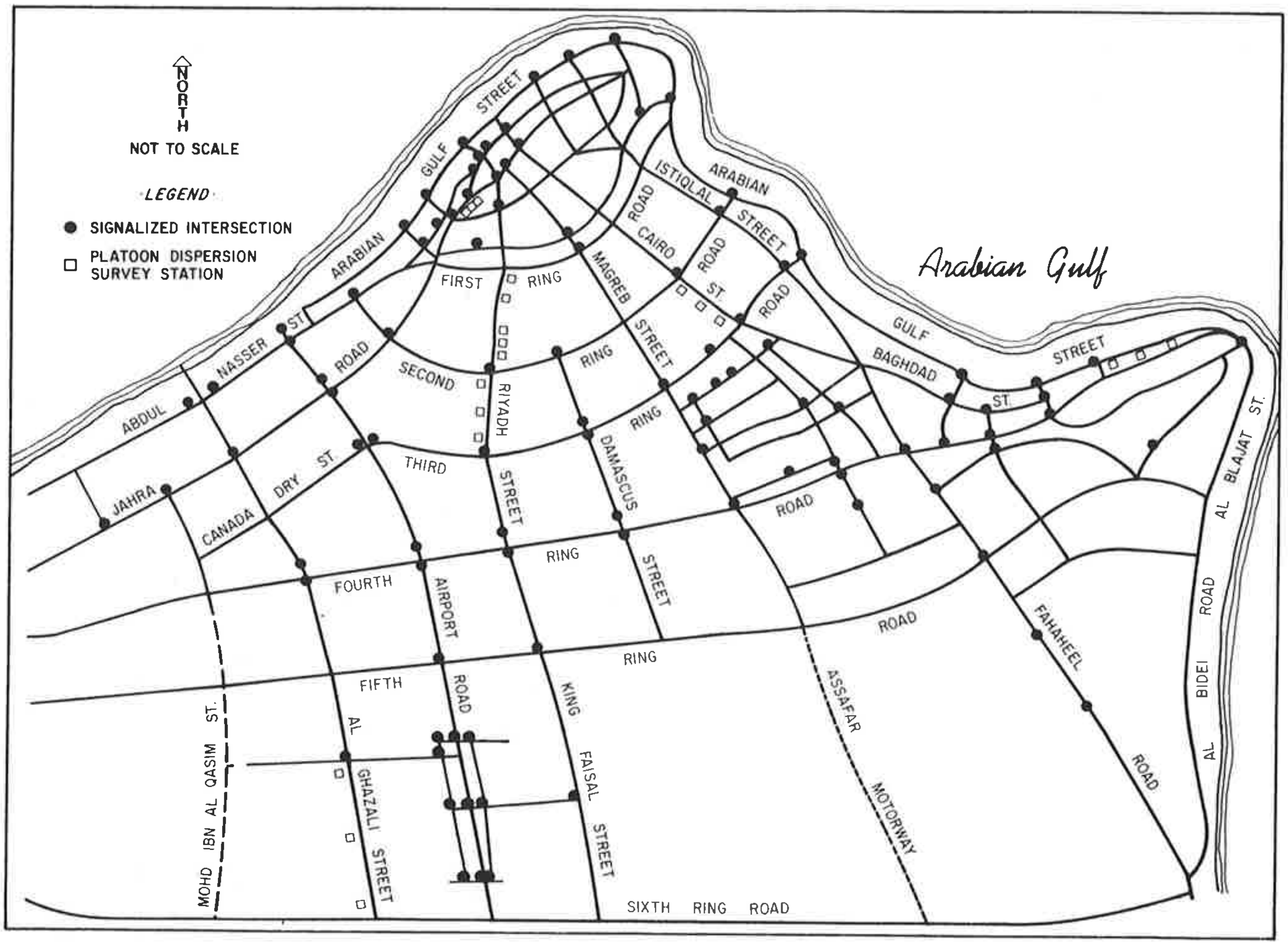

FIGURE 1 The roadway network in Kuwait.

overhead pedestrian bridges being available at numerous locations. Curb parking is not permitted.

In summary, the intersections of radial and ring roads are separated by divided roadways of high standard, along which traffic is able to travel smoothly and rapidly. Although distances between intersections are greater than normally associated with coordination, the special characteristics described previously encouraged efforts to estimate the likely benefits from coordinated signals on the radial and ring roads. As a first step, a survey was conducted to measure the rate at which platoons of vehicles disperse on the Kuwait road network.

PLATOON DISPERSION SURVEY

The purpose of the survey and subsequent analysis was to measure the extent to which traffic remains within a platoon over long distances and to derive an equation that incorporates Kuwait driver characteristics to predict platoon dispersion for use in signal timing plan calculations.

The surveys were conducted along a number of arterial roads and on Fahd Al-Salem Street in Kuwait Town. Six staff members were paired up into counting teams A, B, and C. A seventh staff member operated on his own, monitoring the green signal that released the platoon of traffic to be measured. A schematic diagram that illustrates the typical disposition of field staff is shown in Figure 2. Team A was positioned close to the exit of the signalized intersection, generally just after the right-turn loop entered the main road. Teams B and C were located downstream of A at varying distances from A up to 2.2 km.

Each team and the signal observer were equipped with a synchronized clock. At a preset time, each team commenced its duties. One member of each team counted traffic for periods of 5 sec. To assist him, he was provided with his own clock, which emitted a sharp tone every 5 sec. On hearing the tone, he was to call out the count from the last 5-sec period and this was then recorded by the second team member. Each survey was conducted for 30 min. Average journey times were also measured between the positions of teams A, B, and C by the moving observer method.

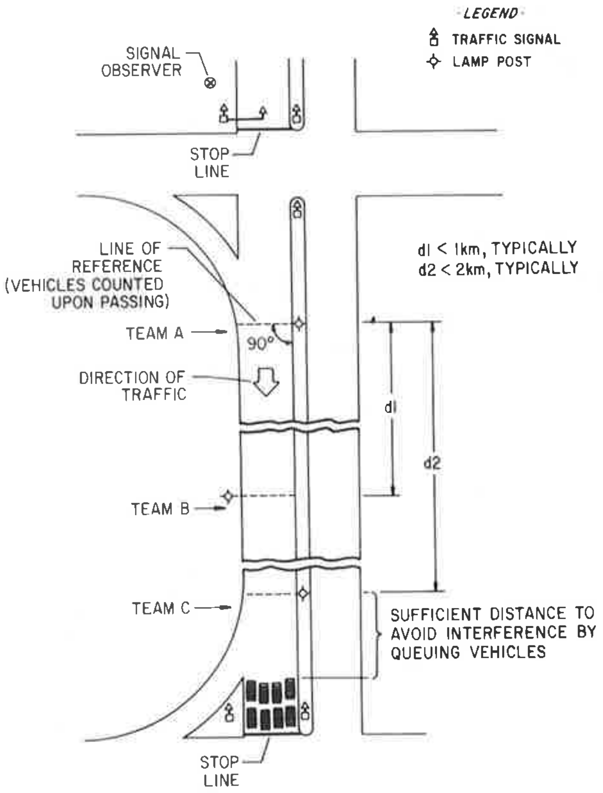

FIGURE 2 Position of observers for platoon dispersion survey.

Survey locations were chosen to permit analysis over as wide a range of distances as possible. To ease subsequent analysis, preference was given to locations with the following features, although these were by no means present in all cases (a) left turns not permitted from the cross street at the upstream intersection, (b) low volumes of traffic entering or leaving the main road between survey stations, and (c) signal controller at the upstream intersection operating in fixed-time mode.

It should be emphasized that the first two criteria were adopted to isolate, to the maximum extent possible, the platoon dispersion phenomenon to be measured. It was, of course, recognized that turning movements at both the upstream intersection and along the road itself have an important bearing on the subject of coordination and benefits that may be derived.

The locations used in the platoon dispersion survey are listed in Table 1. The surveys conducted on Fahd Al-Salem Street were included to permit the platoon dispersion rates on the arterial roads of Kuwait to be compared with those in Kuwait Town.

PLATOON DISPERSION ANALYSIS

One of the most widely used models of platoon dispersion is contained within the TRANSYT signal timing program developed by the Transport and Road Research Laboratory (TRRL) in England (1). This model predicts the number of arrivals in an interval of time at a point downstream of a signalized intersection by use of the following equation:

$$Q'_{i+t} = [Q_i \times F + Q'_{i+t-1} \times (1 - F)] \qquad (1)$$

where

Q'_{i+t} = number of arrivals in interval i + t at a point downstream of a signalized intersection,
Q_i = number of departures in interval i from the signalized intersection,
F = function of journey time between the intersection and the downstream point, and
t = 0.8 x the average journey time, expressed in intervals of time.

The smoothing factor F is expressed as

$$F = 1/[1 + (K \times t)/100] \qquad (2)$$

where K is a constant.

The value recommended for K in the TRANSYT documentation for the original program and in versions through, to, and including TRANSYT 7 is 50 (1-3). This value has since been revised by TRRL to 35 (4). In Release 3 of TRANSYT 7F, issued by FHWA, 35 is the default value and a value in the range from 25 to 50 is suggested depending on roadway characteristics (5).

Analysis of observations was conducted in such a way as to be compatible with the structure of the TRANSYT dispersion formula. This was conducted to permit a comparison to be made of the predictions of the TRANSYT model and observed conditions on the arterial roads in Kuwait. The principal steps in the analysis may be summarized as follows:

TABLE 1 Location of Platoon Dispersion Surveys

		Features		Location (teams B and C)			
Station No.	Location (team A)	Left Turns	Signal Control	Station No.	Distance D1 (m)	Station No.	Distance D2 (m)
1	Riyadh Street south of Second Ring Road	Banned[a]	Fixed	2	430	3	953
2	Cairo Street south of Second Ring Road	Allowed	Police	5	600	6	931
7	Riyadh Street north of Second Ring Road	Banned[a]	Fixed	9	551	11	1343
7	Riyadh Street north of Second Ring Road	Banned[a]	Fixed	8	168	10	953
12	Fahd Al-Salem Street east of Hilali Street	Allowed	Fixed	13	130	14	260
12	Fahd Al-Salem Street east of Hilali Street	Allowed	Police	13	130	14	260
15	Ghazali Street south of Jordan Street	Allowed	Fixed	16	1100	17	2200
18	Arabian Gulf Street westbound between Qatar and Salem Al-Mobarak	Allowed	V/A	19	1000	20	2000

Note: V/A = vehicle-actuated.
Source: Wilbur Smith and Associates, Columbia, S.C.

[a] Left turns were banned at these survey locations, but illegal left turners were observed and counted by survey team A.

1. Calculate the average observed platoon shape at each survey station (i.e., calculate the number of vehicles that passes a station in each 5-sec interval) in the average signal cycle and plot the resulting platoon.
2. By using Equations 1 and 2, calculate predicted flows in each time interval that pass the downstream survey stations, where Teams B and C are located, from the average platoon observed by Team A by using various values of platoon dispersion factor K.
3. Compare the predicted platoons with the platoons observed by Teams B and C.

Sample Analysis of Observed Platoons on Riyadh Street

The number of vehicles that passes a station in each time interval within the signal cycle was averaged over the 30-min period of the survey. With cycle times of 2.5 to 3 min being used, the average platoon shape at a station was therefore derived over approximately 10 signal cycles. The average platoons observed at Stations 1, 2, and 3 on Riyadh Street south of the Second Ring Road (southbound) are shown in Figure 3.

Predicted platoon shapes at the downstream survey stations, B and C, were calculated by using the TRANSYT formula for a number of alternative values of K. The values of K investigated were 50, 40, 35, 30, and 20. For each alternative predicted platoon, a measure of the prediction's degree of similarity with the observed platoon was calculated. This measure was expressed as the sum of the squares of the differences between observed and predicted flows in each increment of time.

The dispersion factor for which the prediction measure was a minimum was taken as the most suitable value. Let this value of K be called K_{min}. Two predicted platoons were then plotted with the observed platoon at the downstream team locations (B and C). These platoons were predicted with K equal to 50 (the original standard TRANSYT value) and K equal to K_{min}. Predicted platoons are shown in Figure 4 for southbound traffic on Riyadh Street.

It can be seen that the value of K = 50 predicts a slightly greater degree of platoon dispersion than was observed during the survey on Riyadh Street. A smaller value of K in the TRANSYT formula, in this case 30, leads to a predicted platoon in closer agreement with the observations made.

The shape of the average platoon as it leaves a signalized intersection is an essential input to the TRANSYT platoon dispersion formula. To derive a meaningful average platoon from the observed data, the analysis described earlier was restricted to those survey sites for which the upstream intersection controller was operating in a fixed-time mode.

The value of the constant K_{min} found for each survey station is shown in Table 2. Also shown are the measured travel times to each station and the average speeds between survey stations.

Prediction of Platoon Dispersion on Roads in Kuwait

Observations made in this survey indicate that the form of equation in the TRANSYT program for modeling platoon dispersion is suitable for predicting dispersion along arterial roads in Kuwait. Different values of K in the TRANSYT formula yielded predicted platoon patterns that were basically similar to each other. The small differences that were obtained were those to be expected from examination of the TRANSYT equation. A smaller value of K results in a larger factor F and, hence, a prediction of greater platoon cohesion (or less dispersion) than larger values of K.

A value for K of 50 was found to be the most suitable for predicting platoon dispersion on the arterial Gazhali Street and on Fahd Al-Salem in the CBD. It is thought that the the free flowing conditions on Gazhali Street, which are normally conducive to a high degree of platoon cohesion, may have been offset by the extremely high speeds, averaging 90 km/hr. On Riyadh Street, platoons were found to retain their formations to a slightly greater extent and a K value between 30 and 40 was found to be more appropriate. Despite the very wide range of distances surveyed (168 to 2200 m), these values of K are in line with the values commonly used in many urban road networks with distances between intersections in the more common range of 100 to 500 m.

The TRANSYT program permits the rate of platoon dispersion to be specified on an individual road link basis, if necessary, by the optional input of the desired K value. In the absence of this item of data for a link, the program uses a default value of K = 35. The sensitivity of the optimized timings to the value used for K was examined in subsequent analysis.

SENSITIVITY OF TIMING PLANS TO RATE OF PLATOON DISPERSION

The platoon dispersion survey indicated that the rate of dispersion was not constant. On some roads the rate was observed to be equivalent to the TRANSYT dispersion factor K of 50. On other roads, however, platoons were observed to retain their formations to a slightly greater extent, which corresponds to a K value of 30 or 40.

These findings raised the question of the sensitivity of TRANSYT signal timings to the value of the dispersion factor specified in the program data for

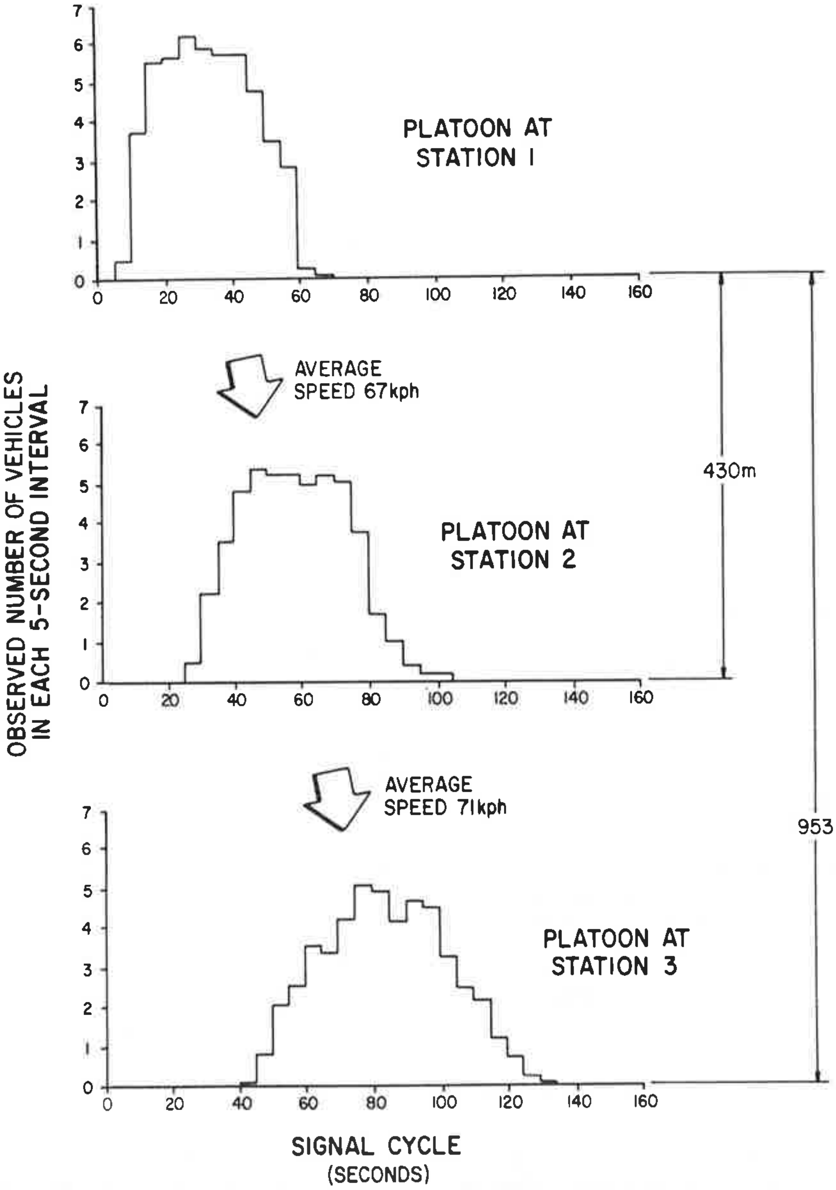

FIGURE 3 Observed platoon dispersion southbound on Riyadh Street between Second and Third Ring Roads.

each link. To examine this sensitivity, data were prepared for a small network, and a total of 18 TRANSYT runs was performed. The network, shown in Figure 5, involved five intersections that correspond to those on Riyadh Street at Second, Third, and Fourth Ring Roads and Damascus Street at Second and Third Ring Roads. The distance between intersections in this network ranged from 1050 to 1450 m.

Description of Analysis

Optimized fixed-time plans were calculated for two sets of traffic flows, which correspond to conditions between 7:00 and 8:00 a.m. and between 5:00 and 6:00 p.m. For simplicity, the following description of nine program runs refers only to the a.m. flows. However, a corresponding set of nine runs for the p.m. conditions was also performed.

An optimized plan was first calculated by assuming that the rate of dispersion along links corresponded to a dispersion factor K of 50. Let the optimum performance index (total delay in vehicle hours per hour plus weighted number of vehicle stops) that results from this plan be denoted by I_{t50}. The weighting factor for stops was given the moderate value of 10 in all runs. A second optimized plan was then calculated by assuming a dispersion factor of 40 and a performance index of I_{t40} was obtained. A final optimized plan for K = 30 was then produced and I_{t30} was calculated. Table 3 shows symbols for the optimized performance indices I_{t30}, I_{t40}, and I_{t50} being positioned as the diagonal elements of a 3 x 3 matrix of performance indices.

A series of six nonoptimizing TRANSYT runs was then performed in which the program merely simulated the effect in terms of delay and number of stops, which would result from a specified set of signal timings. In the first such run, signal timings were fixed at the optimized values found earlier with K = 50, but the link data were such that the simulation model would disperse platoons at a rate equivalent to K = 40. Let the performance index calculated in this run be denoted by $I_{t50/40}$. This symbol is

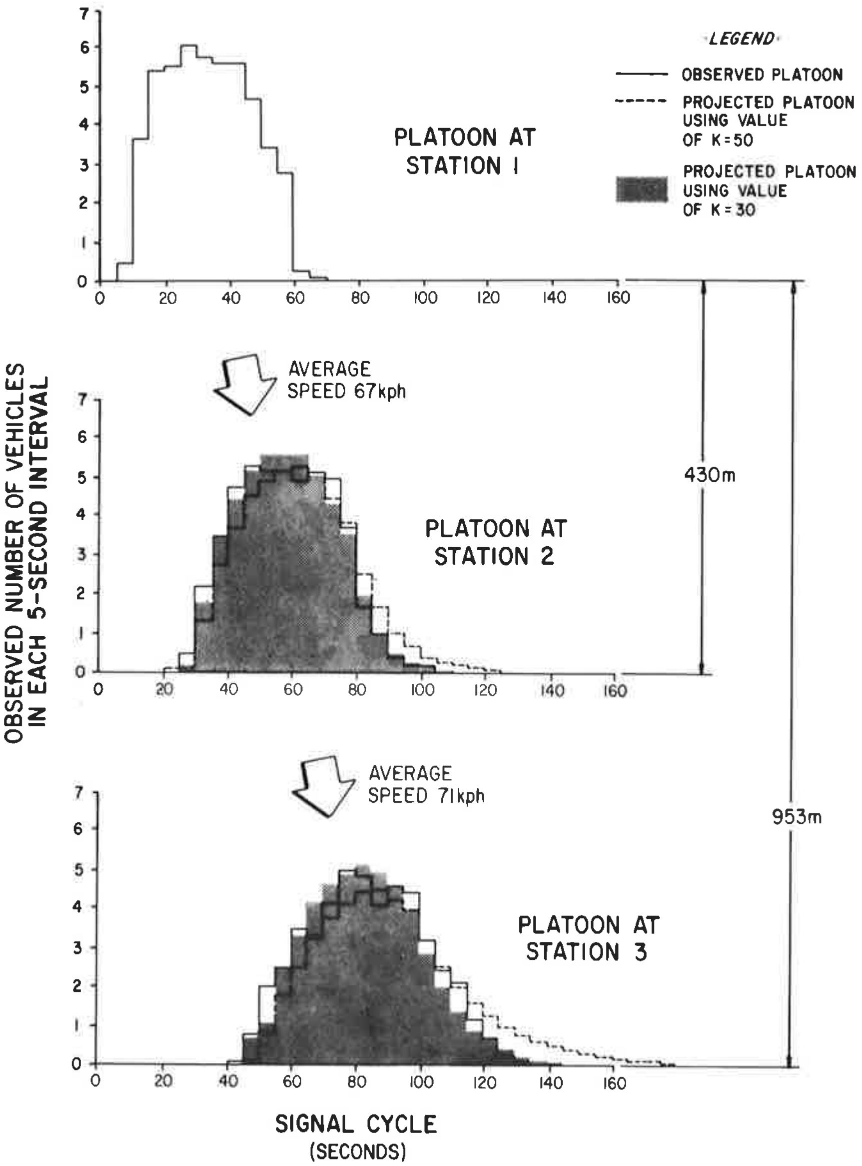

FIGURE 4 Predicted platoon dispersion southbound on Riyadh Street between Second and Third Ring Roads.

TABLE 2 Values of K_{min} Found for Some Arterial Roads in Kuwait

Distance from Location of Team A (m)	Survey Station No. (B or C)	Values of K_{min}	Journey Time (sec)	Average Speed (km/hr)
168	8	35	10.2	59.0
430	2	30	23.0	67.3
551	9	35	30.8	64.4
953	10	30	51.7	66.4
953	3	30	48.2	71.1
1100	16	50	47.5	83.4
1343	11	40	71.5	67.6
2200	17	50	87.8	90.2

shown as the middle element of the top row of the matrix of indices in Table 3. A comparison of the two indices $I_{t50/40}$ and I_{t40} indicates the extra delay and stops that would result from implementing a plan calculated with K = 50 if, in fact, platoons disperse at a slower rate equivalent to K = 40. The extra performance index above the optimum is given in this case by

$$\text{Extra performance index as a percentage of optimum} = 100 \times (I_{t50/40} - I_{t40} \qquad (3)$$

Five further nonoptimizing runs of TRANSYT were performed to calculate $I_{t50/30}$, $I_{t40/50}$, $I_{t40/30}$, $I_{t30/50}$, and $I_{t30/40}$. These symbols are also shown in Table 3.

The numerical values obtained for all nine performance indices calculated during the a.m. peak flow runs are shown in Table 4, and the percentage increases in performance index that would result from each possible combination of fixed-time plan and simulation model assumptions on platoon dispersion rates are given in Table 5. Results for runs with the p.m. flow conditions are given in Tables 6 and 7. Layout of these results in a 3 x 3 matrix follows the format described previously for Table 3.

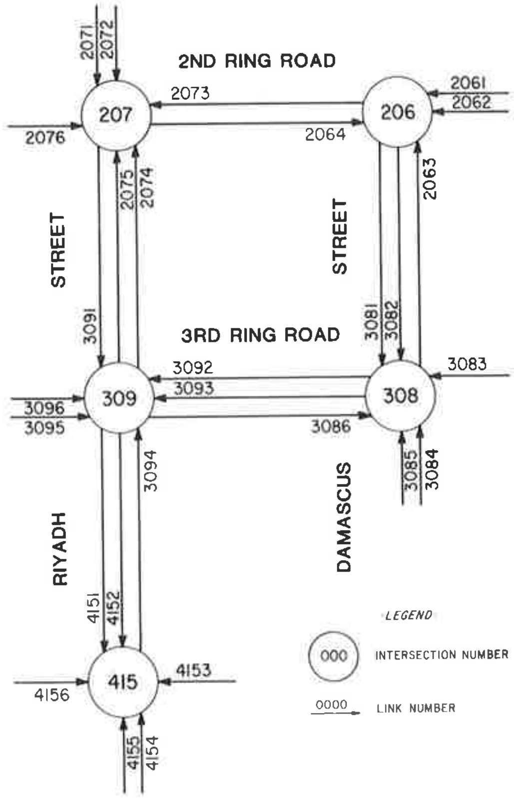

FIGURE 5 Five-intersection network of arterial and ring roads in Kuwait.

TABLE 3 Format for Presentation of Performance Index Values

Signal Timing Plan	Performance Index I by K Value		
	50	40	30
K = 50	I_{t50}	$I_{t50/40}$	$I_{t50/30}$
K = 40	$I_{t40/50}$	I_{t40}	$I_{t40/30}$
K = 30	$I_{t30/50}$	$I_{t30/40}$	I_{t30}

TABLE 4 Sensitivity of TRANSYT Plans to Dispersion Factor K—a.m. Flow Condition Results

Signal Timing Plan	Performance Index I by K Value		
	50	40	30
K = 50	372.58	369.12	366.47
K = 40	372.98	369.03	365.69
K = 30	378.39	372.32	365.38

TABLE 5 Sensitivity of TRANSYT Plans to Dispersion Factor K—a.m. Flow Condition Percentage Increase in Performance Index Above Optimum Value

Signal Timing Plan	Percent Increase in I by K Value		
	50	40	30
K = 50	–	0.02	0.30
K = 40	0.11	–	0.08
K = 30	1.56	0.89	–

TABLE 6 Sensitivity of TRANSYT Plans to Dispersion Factor K—p.m. Flow Condition Results

Signal Timing Plan	Performance Index I by K Value		
	50	40	30
K = 50	285.32	282.50	280.00
K = 40	286.61	282.38	280.42
K = 30	285.61	282.46	279.38

TABLE 7 Sensitivity of TRANSYT Plans to Dispersion Factor K—P.M. Flow Condition Percentage Increase in Performance Index Above Optimum Value

Signal Timing Plan	50	40	30
K = 50	–	0.04	0.22
K = 40	0.45	–	0.37
K = 30	0.10	0.03	–

Results of Sensitivity Analysis

The results indicate that the TRANSYT optimized plans are not particularly sensitive to the value used for the platoon dispersion factor K, in the 30 to 50 range. In only one of the cases examined would an incorrect assumption concerning platoon dispersion rates lead to additional delay and stops in excess of 1 percent of the optimum value.

This is not to say, of course, that different dispersion rates in this range do not produce noticeably different patterns of arrival at downstream stop lines. For example, the results indicate that for a given set of timings, the delay and stops may be up to 3.6 percent greater if dispersion is at the rate equivalent to K = 50 compared with the slower rate of 30 (see indices $I_{t30/50}$ and I_{t30} for a.m. flow conditions). However, these differences in arrival patterns gave rise to optimized plans whose timings differed from each other by only a very small amount. One of the reasons for this may be that although the timing optimization program may find benefits in increasing the percentage of green time for a link whose arriving platoon is more dispersed, there may be liabilities to other links at the same intersection when their green time is correspondingly decreased.

In effect, the requirement to minimize delay throughout the whole network, and not merely on an individual link, acts as a constraint on the potential sensitivity of TRANSYT plans to platoon dispersion rates. The result obtained suggest that for a wide variety of network configurations and characteristics, the use of the default platoon dispersion factor of 35 is quite adequate. The optimized timings found by TRANSYT appear to be sufficiently insensitive to the precise value of this factor that most users can expect satisfactory results by utilizing the program's default value.

COORDINATION BENEFITS ON ARTERIAL AND RING ROADS

To provide support for a judgment on likely benefits from the coordination of traffic signals on the long arterial and ring roads in Kuwait, a number of TRANSYT computer runs were performed to calculate delays on road links, first assuming that the signals at both ends of the link were coordinated and second, that they were not. Road lengths, traffic flows, signal phasing, saturation flows, and cycle times typical of Kuwait were utilized in preparing the data for these runs.

The rate of platoon dispersion assumed in these computer runs equaled the fastest rate observed during the platoon dispersion survey--the rate corresponding to a K value of 50. The fastest observed rate was used to provide a conservative estimate of the benefits as a result of coordination.

It should be noted that estimated benefits were based on a comparison of coordinated control with uncoordinated operation on the same cycle time. They therefore did not fully reflect the advantages of a modern traffic control system that permits timing plans with optimum cycle lengths to be implemented as traffic conditions change through the day--a facility not available with most existing fixed-time controllers in Kuwait.

Five-Intersection Arterial Network

The five-intersection network referred to earlier was included in a variety of performed runs. For this network, two optimized plans were calculated to cater to traffic conditions between 7:00 and 8:00 a.m. and between 5:00 and 6:00 p.m. Cycles of 150 and 120 sec were used for the morning and evening plans, respectively. The delays at traffic signals with these plans are given in Table 8 and are compared with the delay calculated if the signals were uncoordinated.

Links that feed intersections from outside the network are not able to derive any benefits from coordination. Considering only the internal links, therefore, the reduction in delay with coordination amounts to 18.4 and 19.6 percent in the morning and evening plans respectively. However, in this small network there are as many external links as internal; when all links in the five-intersection network are considered, the reductions in delay fall to 10.8 and 10.1 percent, respectively.

Estimated Benefits

The TRANSYT runs confirmed that reductions in delay as a result of coordination of signals diminish as the distance between signals increases. However, reductions in delay were still found to be significant over the range of road lengths (500-2000 m) examined.

On road links between 1000 and 1500 m long, reductions in delay of up to 20 percent were estimated with coordinated signal timings compared with uncoordinated control. Roads in this length range occur frequently in the arterial road network in Kuwait between the First and Fourth Ring Roads. A greater reduction in delay may be expected within Kuwait Town where link lengths are much shorter, but less improvement may be obtained on and beyond the Fourth Ring Road where distances between intersections are greater.

With the inevitable break in coordination on roads that span subareas that are operating on different cycle times, the overall network-wide reduction in delay will be less than that for individual coordinated links. The characteristics of the Kuwait road network are such that, at times, the number of different cycle times in operation may be greater than that in many coordinated traffic signal systems with a similar number of intersections. It was therefore considered that a network-wide reduction in delay of 10 percent represented a reasonable, conservative estimate of the improvements that could be obtained from the coordination facilities provided by a modern traffic signal system.

TABLE 8 Reduced Delay with Coordination on a Five-Intersection Arterial Network in Kuwait

Traffic Flow	Delay by Type of Signal (vehicle-hr/hr) Uncoordinated	Coordinated	Reduction in Delay (%)
7-8 a.m.			
Links internal to network	205.7	167.8	18.4
All links in network	350.7	312.8	10.8
5-6 p.m.			
Links internal to network	133.6	107.4	19.6
All links in network	258.4	232.3	10.1

SUMMARY

The work described previously, which was undertaken during a feasibility study of a traffic signal system for the city of Kuwait, demonstrated that platoons of traffic remain grouped over distances of up to 2000 m on the arterial and ring roads in the urban area. These roads are 6-lane divided roadways of high standard with little in the way of friction effects to disturb the smoothness of flow.

Measured rates of platoon dispersion were found to be equivalent to a TRANSYT platoon dispersion factor in the range of 30 to 50. Use of the TRANSYT model indicated that optimized signal timings are not sensitive to the value assumed for K in this range. Based on these observations, it was conservatively estimated that delays at traffic signals may be reduced by at least 10 percent through coordination of signals on the arterial and ring roads of Kuwait, where intersections are 1000 to 1500 m apart.

The results demonstrated that the distance between signalized intersections is not necessarily an adequate reason for disregarding the potential benefits of coordination. Where friction effects are small and platoons are readily identifiable as they approach the downstream intersection, coordination may be beneficial even over long distances.

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Discussion

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Appropriate traffic coordination can guide the random traffic flow into a compact platoon, control travel speeds, and provide safe crossing gaps for efficient traffic operations. Platoon dispersion of vehicles that travel between signalized intersections can reduce the potential benefit of traffic

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signal coordination. This paper took a major step in analyzing the sensitivity of the platoon dispersion factor on the optimized traffic signal timing settings.

An interconnected signal system can result in a controlled nonuniform traffic flow during different signal cycles. If progression between signals is good, most of the traffic will arrive at the downstream intersection in a progression platoon during the green signal phase. This phenomenon can best be observed through the average arrival rate in the green phase, which is greater than the average arrival rate during the red phase. On the other hand, poor progression could result in a greater arrival rate during the red phase than that during the green. The percentage of an approach's through traffic coming from an adjacent upstream intersection and arriving during the through green at the downstream intersection depends principally on three factors: (a) percent of the total traffic that is in the progression platoon, (b) size and rate of platoon dispersion, and (c) quality of platoon progression between the two intersections. The percent volume progressed can be calculated from the product of (a) percent of the total through traffic in the arterial direction, (b) length of platoon leaving the upstream intersection, and (c) time period for the through movement saturation flow to clear at the upstream intersection in the arterial travel direction.

The platoon length that arrives at the downstream intersection depends on (a) the original platoon length that left from the upstream intersection, (b) the average travel time between the intersections, and (c) the number of vehicles in the platoon. The platoon dispersion rate increases with increasing travel time between intersections and small platoon size.

The progression quality of platoons between two intersections could best be described by the location and the amount of the through green time being used by the progression bandwidth. The period during which the progressed platoon occupies the through green at the downstream intersection depends on (a) the platoon length that arrives at the downstream intersection, (b) the length of the through green time at the downstream intersection, and (c) the progression quality between these two intersections. The optimal calculated arterial progression time-space diagram calculated can be used to examine the quality of progression between the intersections. Good progression would result in a larger progression bandwidth, whereas bad progression might result in either a smaller progression bandwidth or no progression bandwidth.

From this study and the similar research made by the Texas Transportation Institute under HP&R Study 2-18-80-293, supported by the Texas State Department of Highways and Public Transportation, the following comments may be made:

1. Platoon dispersion factors are affected by the approach speed of vehicles that enter and leave the studied intersections.
2. The use of upstream intersection control strategies can affect the progression platoon on the downstream intersection. Arterial traffic operations on high-speed, short-link roads tend to keep platoon travel together.
3. A periodic relationship was observed between the arterial specific link delay, and the ratio of travel time versus cycle length provides a better estimate of the arterial link delay than would the travel time alone.
4. Disutility or the resultant signal delay can be redistributed in the network by the platoon progressed between intersections. The adjustment of combining offsets and the green time to allow more favorable travel directions can further improve the efficiency of the traffic flow on arterial signal systems.
5. This study again raises the question of whether the intersections at certain distances can benefit from the time-based coordination.
6. What are the effects of platoon dispersion on the quality of progression? How valid is the bandwidth theory related to the progression efficiency as disturbed by the dispersion of platoon progressing through the downstream intersections? What is the best method for measuring progression quality that reflects platoon dispersion on signalized arterial networks?

Author's Closure

In summary, the theory that estimation of interconnect feasibility on the basis of link lengths alone is an oversimplification and that other roadway characteristics can be significant is confirmed in this study. Also demonstrated is the theory that use of the TRANSYT program's default value for the rate of platoon dispersion is adequate for a wide range of conditions. The majority of users need not, therefore, invest valuable data collection, time, and money in measuring platoon dispersion rates on their own road networks.

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Comparative Analysis of Computer Models for Arterial Signal Timing

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ABSTRACT

The state-of-the-art computer models TRANSYT-7F, MAXBAND, and PASSER-II for arterial signal timing are evaluated considering their capabilities in developing optimal timing plans, input data requirements, and output options. These models were applied on an 11-signal arterial to optimize various combinations of the signal control variables for two-phase and multiphase signal operation. It was found that the timings from TRANSYT-7F were better in terms of traffic performance than the settings from the bandwidth models, under fixed phasing. The settings from MAXBAND and PASSER-II produced very similar results. A number of experiments were also performed to investigate ways for concurrent use of the programs to further improve signal timing. The results indicated that the optimization capabilities of TRANSYT-7F can be improved if the input cycle length and sequence of phases have been optimized with the other models. Suggestions are made for improving the optimization capabilities and the practical application of the selected models.

Signal timing optimization is one of the most efficient ways for reducing fuel consumption and improving traffic operations on urban arterials and networks (1,2). A statewide Fuel Efficient Traffic Signal Management (FETSIM) program is currently under way in California that provides grants to local agencies to optimize their signal systems. Forty-one cities participated in the 1983 FETSIM program, which involved retiming 1,535 signals. The benefits included savings of nearly 6 million gal of fuel and significant reductions in delays and stops (3). The overall first year benefit-cost ratio was 16 to 1, which demonstrates the cost-effectiveness of optimizing the timing plans of existing signal systems.

Several computer models have been developed for improving traffic signal timing. A literature search revealed the following models as readily available, well-documented, and in use for signal timing optimization and evaluation: TRANSYT-7F, PASSER-II(80) MAXBAND, NETSIM, SOAP/M, and SPAN. Other programs under development include the SIGOP-III model, and the Arterial Analysis Package (AAP).

Initial examination of these models showed that TRANSYT-7F, MAXBAND, and PASSER-II can be used directly to determine optimal signal settings on signalized arterials. NETSIM is a stochastic microscopic network simulation model (4). It simulates individual vehicle movements according to car-following, queue discharge, and lane changing laws, and predicts delay, number of stops, fuel consumption, and emissions. NETSIM cannot optimize signal timing; it is most suited as a tool to evaluate alternative control strategies (i.e., pretimed and traffic-adjusted signal control) and to test the effectiveness of different optimization techniques. SOAP/M (5) provides optimal timing at isolated intersections, based on Webster's method (6). This program is particularly useful to determine the number of phases at each signal, and it may be used as an auxiliary tool for timing arterial systems. SPAN may be also considered as an auxiliary program. It optimizes only offsets on an arterial, considering local progression, such as bands that do not extend throughout the system (5).

The TRANSYT-7F model (7,8) has been used as the basic tool in most of the signal retiming projects. The PASSER-II model (9) is increasingly being used for arterial signal timing, and Rogness (10) reported that PASSER-II produces good timings compared with TRANSYT-7F. Recent results reported by Cohen (11) showed that the MAXBAND model (12) gives effective timing plans and substantially enhances the optimization capabilities of TRANSYT-7F when these programs are used concurrently. Concerns have also been raised by practicing engineers that TRANSYT-7F is a complicated program to use, and it does not provide the maximum bandwidth, which historically is the popular solution to the arterial coordination program.

The study described in this paper has two objectives: (a) to evaluate the state-of-the-art computer models for arterial signal timing, considering their capabilities in optimizing the signal control parameters, input data requirements, and output options; and (b) to investigate ways for concurrent use of these computer models to assist the traffic engineer to select the best timing plan for an arterial signal system.

The TRANSYT-7F, PASSER-II, and MAXBAND models are evaluated and their strengths and weaknesses are discussed. Next the results from the application of the selected models on a test arterial are presented. In the last section the findings from the study are summarized and recommendations for further research are given.

DESCRIPTION OF THE MODELS

TRANSYT-7F is a macroscopic deterministic simulation and optimization model, which operates in two modules. The traffic model uses network geometry, traffic volumes, and dispersion of traffic platoons to simulate the existing conditions along an arterial or network of signals and estimates performance by using a set of measures of effectiveness (MOEs)--travel time, delay, stops, and fuel consumption. The signal optimizer uses a hill-climbing technique to adjust splits and offsets to minimize a performance index (PI), which is a linear combination of delays and stops. The optimization process uses an iterative gradient search algorithm and does not guarantee that the true optimal signal settings will be obtained.

MAXBAND can be classified as a macroscopic optimization model. It uses mixed-integer linear programming to simultaneously optimize cycle length, sequence of phases, and offsets to maximize the bandwidth in both directions of an arterial. The optimization algorithm guarantees that the global optimum solution will be found. Splits are not optimized because the bandwidth approach does not provide criteria for setting green times on the side streets. The model allows for directional bandwidth weighting and deviation of the overall progression speed on individual links. Modeling of traffic flow does not account for turning volumes, dispersion and shape of platoons, and secondary traffic volumes.

PASSER-II is also a macroscopic optimization model, based on the bandwidth principle. It provides the best phasing sequences and offsets for maximal bandwidth along an arterial by minimizing the sum of interferences to the bandwidth (13). The optimal cycle length is obtained from multiple computer runs. Splits are calculated for minimum delay at each intersection on the basis of a modified Webster's delay formula (6). The model also allows for variations in the overall progression speed and weighting of the directional bands. Modeling of traffic flow is similar to that with the MAXBAND model.

COMPARISON OF THE MODELS

This section contains a discussion on the application of the selected models to develop optimal signal settings and their respective strengths and weaknesses. Table 1 contains a summary of the capabilities of the models regarding the optimization of the control parameters, for example, the number of phases, sequence of phases, cycle length, phase lengths (splits), and offsets.

Development of Signal Timing Plans

The number of phases at each signal is input to all arterial models. The determination of the number of phases is commonly based on volume, delay, and safety criteria at the particular intersection. SOAP/M may be used to analyze the impact of different numbers of phases. However, it should be noted that no computerized or manual procedure exists for the determination of the number of phases that include consideration of the system performance, and adding phases to improve the operation of a particular intersection may create adverse impacts for the entire arterial. There is a need to develop and incorporate a procedure into the existing arterial models to predict these system-wide impacts and to assist in the selection of the number of phases.

TABLE 1 Optimization of Control Variables with the Selected Models

	Model		
Control Variable	TRANSYT-7F	MAXBAND	PASSER-II
Number of phases	Input	Input	Input
Sequence of phases	Input	Optimized	Optimized
Cycle length	Optimized[a]	Optimized	Optimized[b]
Splits	Optimized	Computed[c]	Optimized
Offsets	Optimized	Optimized	Optimized

[a] No explicit optimization; range of cycle lengths is examined and the one with the lowest PI is selected.

[b] Optimization is performed through multiple runs.

[c] Splits are computed for equal degrees of saturation.

The sequence of phases may consist of numerous combinations of protected and permissive movements, such as leading left turns, lagging left turns, and combinations of lead/lag operation. Other options include permissive-protected or protected-only operation, and unprotected movements. PASSER-II and MAXBAND directly optimize phase sequences with and without overlapping to maximize arterial progression. Phase sequences are required inputs to TRANSYT-7F. Repeated runs are needed to evaluate alternative phase sequences that are selected manually by examination of the flow profiles and time-space diagrams. Protected-permissive operation may be approximated in all models by using only the protected phase for the left turns, such as considering the protected left-turn phases and volumes. Unprotected only operation can be approximately modeled with TRANSYT-7F. MAXBAND and PASSER-II do not explicitly consider left-turn volumes unless a separate left-turn phase is present.

MAXBAND directly optimizes the cycle length for maximum bandwidth. PASSER-II optimizes the cycle length through repeated runs, and the optimal cycle is selected on the basis of the bandwidth efficiency. TRANSYT-7F does not explicitly optimize the cycle length; it evaluates a range of values and selects the cycle that results in the lowest PI after splits and offsets have been optimized. TRANSYT-7F also allows for double cycling where some signals operate on a cycle that is one-half the system cycle length.

Phase lengths (splits) are optimized in TRANSYT-7F for minimum stops and delay in the system. PASSER-II optimizes splits for minimum delay at each intersection after the maximum bandwidth has been established. MAXBAND does not optimize green times; splits may be input or computed to equalize the degrees of saturation on the conflicting critical approaches.

In offset optimization, the objective of both PASSER-II and MAXBAND is to find the offsets that maximize the weighted sum of the directional green bands on an arterial. TRANSYT-7F optimizes offsets to minimize the delays and stops in the system, and the solution may not produce the wide green bands preferred by a number of traffic engineers. The opposite is true for the bandwidth models; maximizing through progression does not necessarily result in systemwide minimum delays and stops.

Another parameter of interest in signal timing is the intergreen interval, that is, the yellow and any all-red periods. These values are usually predetermined on the basis of local conditions. TRANSYT-7F, because it deals explicitly with traffic flow, can analyze the impacts of intergreen intervals as well as the effects of start-up, lost time, and green extension. The other models have default values that cannot be changed. TRANSYT-7F also allows the division of splits into fixed and variable intervals, such as Walk and Flashing Don't Walk.

Input Requirements and Output Options

All models operate on mainframe computers and require structured coding of the input data. TRANSYT-7F and PASSER-II also run on 16-bit microcomputers. TRANSYT-7F can handle up to 50 intersections in a line or a grid network, whereas PASSER-II and MAXBAND can accommodate up to 20 signals along an arterial. MAXBAND can also handle triangular networks for up to 17 nodes. Table 2 contains a summary of the input requirements for all models, and the output from each model is given in Table 3.

TRANSYT-7F requires a substantial amount of data, including network geometry, turning movements at each intersection, saturation flows, link-to-link volumes, speeds, and signal timing data. The network should also be coded into a link-node scheme. Although TRANSYT-7F has American terminology of signal settings, and input data are grouped per intersection, data processing and input coding require a substantial effort. Data on traffic performance are also needed to calibrate the model before the timing plans are optimized. TRANSYT-7F, however, gives the most complete output of traffic performance and signal settings. Information on several MOEs is given for each link and summarized for each intersection and the whole system. Signal controller tables are printed to facilitate field implementation of the optimized signal timings. The model provides both flow profiles and time-space diagrams for visual inspection of the quality of the signal settings. Interpretation of the output is relatively straightforward; the main problem areas seem to be understanding the estimates of the maximum back of queue, random delay, and the meaning of the flow profiles.

TABLE 2 Input Data Requirements for Signal Optimization Models

	Model		
Input Data	TRANSYT-7F	MAXBAND	PASSER-II
Network data			
Number of signals	X	X	X
Intersection spacing	X	X	X
Timing data			
Cycle length	X^{a}	X^{a}	X^{a}
Number of phases	X	X	X
Sequence of phases	X	X^{b}	X^{b}
Splits	X^{c}	X^{d}	X^{e}
Offsets	X^{c}		
Minimum green times	X	X^{b}	X
Lost time	X		
Queue clearance		X^{b}	X^{b}
Volume data			
Saturation flows	X	X^{b}	X
Turning movements	X	X^{b}	X
Link-to-link volumes	X		
Speed data			
Free speeds	X	X	X
Speed tolerance		X^{b}	X^{b}

[a] Range (a single value may also be input).
[b] Optional.
[c] The STAR1 routine is used to generate initial timings.
[d] If splits are not input, then volumes and saturation flows are required.
[e] Existing splits may be used for minimum green times to optimize offsets.

TABLE 3 Output from Signal Optimization Models

	Model		
Output	TRANSYT-7F	MAXBAND	PASSER-II
Traffic performance			
Delay for each movement	X		X
Delay per intersection	X		X
Total system delay	X		X
Number of stops	X		
Fuel consumption	X		
Travel time	X		
Degree of saturation	X		X
Maximum back of queue	X		
Level of service			X
Queue clearance			X
Signal settings			
Cycle length	X	X	X
Phasing sequence	X	X	X
Splits	X	X	X
Offsets	X	X	X
Interval lengths	X		
Graphical output			
Flow profiles	X		
Time-space diagram	X		X
Other			
Progression speed		X	X
Bandwidth		X	X

Note: Output on basis of information at the time of study.

Field data required for PASSER-II to produce a complete timing plan are similar to that for TRANSYT-7F, namely, distance between signals, turning movements, saturation flows, cruise speeds, and minimum green times. The model does not require link-to-link volumes, and the input coding is considerably simpler than that for TRANSYT-7F. PASSER-II provides information on the degree of saturation, average delay, level of service, and probability of queue clearance for each approach, total delay for each intersection, and the total system delay. The output also gives the optimal signal settings and a time-space diagram including the green bands and the progression speed. The form of the output is familiar to most traffic engineers, and the results can be easily analyzed.

MAXBAND requires about the same amount of field data as the other programs: turning movements, saturation flows, minimum green times, intersection spacing, and cruise speeds. If the splits are kept fixed, then the model requires the minimum amount of data compared with the other programs; only signal spacing and speeds are needed. Input coding is straightforward, similar to that for the PASSER-II program. Output from MAXBAND includes the optimized signal settings at each signal, bandwidth, and progression speeds and times along each direction of the arterial. The program does not, however, predict delays, stops, and other MOEs, nor does it provide a time-space diagram. Considerable analysis may be required to interpret the developed plan by either manually constructing a time-space diagram or by using a simulation model to predict traffic performance before field implementation.

APPLICATION OF THE MODELS AND RESULTS

The Study Arterial

San Pablo Avenue, State Highway 123, in Berkeley was selected as the study arterial. This is an important parallel route to the Eastshore freeway system, and also carries a significant number of local buses. San Pablo Avenue extends from Oakland in the south through Berkeley to Albany, El Cerrito, and Richmond in the north. The study section has three lanes in each direction with left-turn bays, a total length of 2.8 miles, and 11 intersections. The average spacing is about 1,500 ft, ranging from 450 to 2,300 ft. Figure 1 shows the intersection spacing and the total volumes on each approach for the system.

All of the 11 signals in the study section have two phases and operate on a common cycle length of 70 sec. The required data on arterial geometry, saturation flows, speeds, volumes, and signal settings were collected in 1983 as part of an Institute of Transportation Studies research project on signal control sponsored by the California Department of Transportation and FHWA. The p.m. peak period was

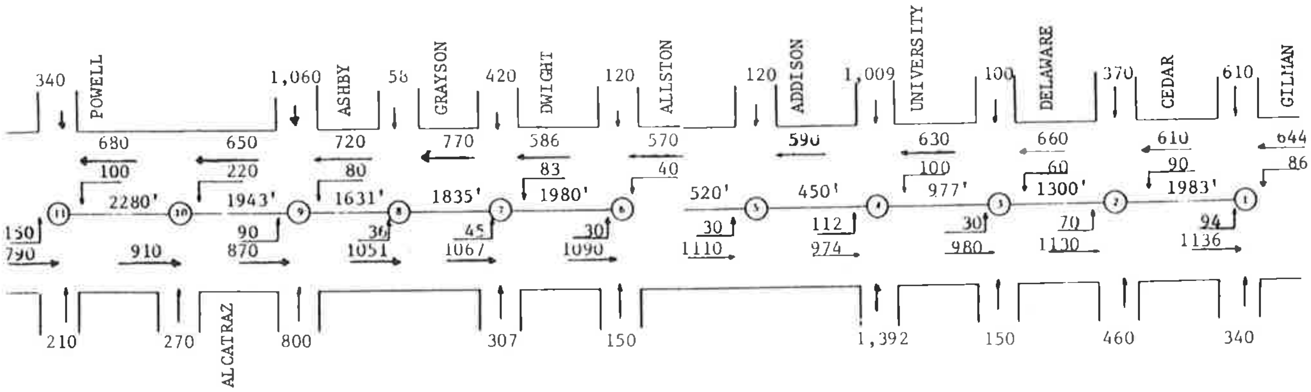

FIGURE 1 San Pablo Avenue: link spacing and traffic volumes.

selected for model applications because of the bad traffic conditions. The average traffic volumes on the arterial were approximately 1,000 vehicles per-hour (vph) in the northbound direction and 700 vph in the southbound direction. Intersections 4 and 9 had high side-street volumes and may be considered as the critical locations. The other intersections had relatively low side-street volumes (Figure 1).

Objective Function

The TRANSYT-7F, MAXBAND, and PASSER-II optimization models were applied to develop improved signal settings for the test arterial, and the performance of the timing plans was evaluated by using the TRANSYT-7F simulation model. The NETSIM model was also used to test the effectiveness of several optimized plans.

PASSER-II and MAXBAND optimize signal timing for maximum bandwidth, which tends to improve perceived progression except the bandwidth is not directly relevant to the TRANSYT-7F objective function. The objective function in TRANSYT-7F for developing optimal timing plans was set for minimum fuel consumption, that is, PI has the meaning of excess fuel consumption as a result of delays and stops, which is expressed as

$$PI = \sum_{i=1}^{n} (k_{1i} d_i + k_{2i} s_i) \qquad (1)$$

where

n = number of links in the system,
k_{1i} = fuel coefficient for delay (gal/hr),
d_i = delay on link i (vehicle-hr/hr),
k_{2i} = fuel coefficient for stops (gal/stop); and
s_i = stops on link i (stops/hr).

This objective function was selected for the following reasons: (a) optimization for minimum fuel was considered important in this study, which was performed in support of the FETSIM program; (b) optimization for minimum fuel tends to provide a reasonable balance between delays and stops (on the average, one stop is equivalent to 25 sec of delay); and (c) experience has shown that the resulting TRANSYT-7F timings provide good progression. The selected objective function would also enable better comparisons with the results of the other models. Optimization for minimum delay tends to overlook stops, and it is more appropriate for dense grid networks than for arterials. It is also known that TRANSYT-7F may provide unacceptable timings when optimized for minimum number of stops.

Experiment 1: Optimization of Splits and Offsets

In this experiment, first the offsets only and then the splits and offsets are optimized for the existing two-phase operation and the common cycle length of 70 sec. The objective of this experiment is to assess the performance of the splits and offsets developed by the selected models and to investigate the effect of using different initial settings in TRANSYT-7F optimization. Summaries of the computer runs performed are given in Table 4, where Run 1 represents the existing conditions. The results of the MOEs are given in Table 5, and the changes in the TRANSYT-7F PI are shown in Figure 2.

TABLE 4 Design of Experiment 1: Optimization of Splits and Offsets for Existing Cycle Length—Two-Phase Scenario

Run No.	Control Variable Optimized	Source of Initial Settings: Splits	Source of Initial Settings: Offsets	Final Optimization
1[a]	—	Existing	Existing	—
2	Offsets	Existing	Existing	TRANSYT
3		Existing	None	MAXBAND
4		Existing	None	PASSER-II
5	Splits/ Offsets	Existing	Existing	TRANSYT
6		Default	Default	TRANSYT
7		None	None	MAXBAND
8		None	None	PASSER-II
9		Existing	MAXBAND	TRANSYT
10		Existing	PASSER-II	TRANSYT
11		MAXBAND	MAXBAND	TRANSYT
12		PASSER-II	PASSER-II	TRANSYT

[a] Existing conditions.

TABLE 5 Results from Experiment 1: Optimization of Splits and Offsets (C = 70 sec)

Run No.	Measures of Effectiveness: Delay (vehicle-hr/hr)	Stops (stops/hr)	Fuel (gal/hr)	PI	Improvement in Performance Index[a] (%)
1	118.36	18,152.8	407.80	190.84	-
2	101.37	15,112.4	376.20	159.22	16.6
3	107.12	16,803.5	390.76	173.83	8.9
4	107.74	16,700.5	390.29	173.36	9.2
5	96.11	14,909.4	369.49	152.73	20.0
6	97.40	14,601.6	368.93	152.19	20.3
7	106.85	16,581.3	388.81	171.95	9.9
8	102.28	16,003.7	381.44	164.63	13.7
9	94.21	14,486.1	366.15	149.44	21.7
10	94.64	14,535.6	360.60	149.87	21.5
11	97.32	15,063.6	371.43	154.71	18.9
12	97.11	15,098.6	371.26	154.51	19.0

[a] From existing conditions.

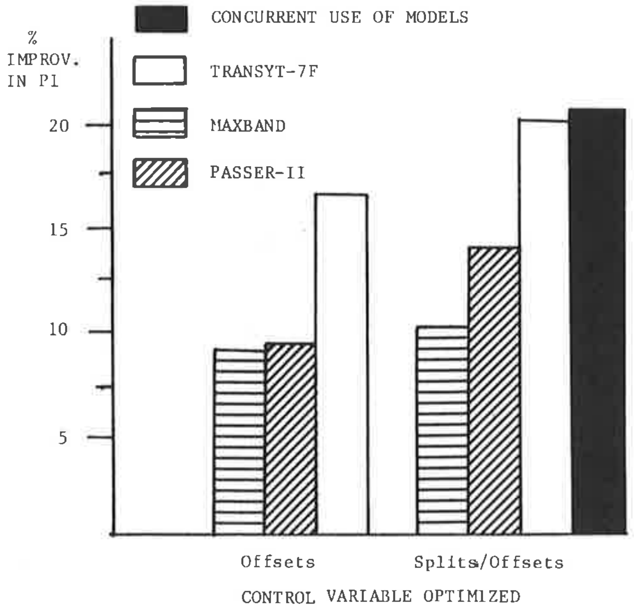

FIGURE 2 Optimization of splits and offsets.

In the offset optimization, with the splits kept fixed as the existing ones, the settings from all models improved the traffic performance. TRANSYT-7F offsets improved the overall system performance by 16.6 percent and the other models by about 9 percent (Figure 2). Comparisons of the results show that the TRANSYT-7F solution was better than those of both MAXBAND and PASSER-II. Delays were less by 6 percent, stops by 10 percent, and fuel by 4 percent. The offsets from the two bandwidth models produced almost identical results in all the MOEs.

When both splits and offsets are optimized (Runs 5, 7, and 8), TRANSYT-7F improved the system performance by 20 percent, whereas PASSER-II improved the PI by 13.7 percent and MAXBAND by about 10 percent (Figure 2). PASSER-II outperformed MAXBAND by 3.5 percent in delays and stops and 2 percent in fuel consumption; this may be attributed to the better procedure in the PASSER-II model for determining signal splits. TRANSYT-7F timings again produced better results than those of the other models. Delays and stops were reduced by 10 percent and fuel consumption by 5 percent compared with the performance of the MAXBAND settings; delays were also reduced by 6 percent, stops by 7 percent, and fuel by 3 percent compared with the PASSER-II timings.

Next, the results obtained from TRANSYT-7F optimizations with starting values for splits and offsets taken as the optimal ones from the other programs were analyzed (Table 5). These results indicate that no substantial improvements were obtained from the concurrent use of the programs compared with the TRANSYT-7F optimum plan from existing settings. The maximum improvement in the PI was about 2 percent (Runs 5 and 9) and the differences in all the MOEs were approximately ±2 percent.

The results from Experiment 1 were further examined by grouping together the values of the PI within 2 percent, assuming that 2 percent is "noise" in the model. The following can be observed for the arterial studied: the best timing plans were all derived by TRANSYT-7F, existing splits provided a better starting solution than the splits produced by the two bandwidth models, and PASSER-II gave the best non-TRANSYT-7F solution.

Experiment 2: Phase Sequence, Split, and Offset Optimization

In this experiment, the programs were applied to develop timing plans for multiphase signal operation to investigate the potential of MAXBAND and PASSER-II to directly optimize the sequence of phases. All signals were assumed to be pretimed with left-turn phases on the arterial. The design of experiment is shown in Table 6. The existing conditions are represented in Run 1, the offsets are optimized in Runs 2 through 4, and the splits and offsets are optimized in Runs 5 through 12, similar to the runs performed in Experiment 1. The sequence of phases and offsets are optimized in Runs 13 and 14. Finally, all the control variables are optimized in Runs 15 through 20. The results are given in Table 7, and the changes in the TRANSYT-7F PI are shown in Figure 3.

In offset optimization, TRANSYT-7F timings improved the PI by 12.3 percent over the existing con-

TABLE 6 Design of Experiment 2: Phase Sequence, Split, and Offset Optimization for Existing Cycle Length—Three-Phase Scenario

Run No.	Control Variable Optimized	Source of Initial Settings			Final Optimization
		Phasing	Splits	Offsets	
1[a]	–	Existing	Existing	Existing	–
2	Offsets	Existing	Existing	Existing	TRANSYT
3		Existing	Existing	None	MAXBAND
4		Existing	Existing	None	PASSER-II
5	Splits/ offsets	Existing	Existing	Existing	TRANSYT
6		Existing	Default	Default	TRANSYT
7		Existing	None	None	MAXBAND
8		Existing	None	None	PASSER-II
9		Existing	Existing	MAXBAND	TRANSYT
10		Existing	Existing	PASSER-II	TRANSYT
11		Existing	MAXBAND	MAXBAND	TRANSYT
12		Existing	PASSER-II	PASSER-II	TRANSYT
13	Phasing/ Offsets	None	Existing	None	MAXBAND
14		None	Existing	None	PASSER-II
15	Phasing/ Splits/ Offsets	MAXBAND	Existing	MAXBAND	TRANSYT
16		PASSER-II	Existing	PASSER-II	TRANSYT
17		None	None	None	MAXBAND
18		None	None	None	PASSER-II
19		MAXBAND	MAXBAND	MAXBAND	TRANSYT
20		PASSER-II	PASSER-II	PASSER-II	TRANSYT

[a]Existing conditions.

TABLE 7 Results from Experiment 2: Optimization of Phase Sequence, Splits, and Offsets (C = 70 sec)

Run No.	Measure of Effectiveness				Improvement in PI[a] (%)
	Delay (vehicle-hr/hr)	Stops (stops/hr)	Fuel (gal/hr)	PI	
1	168.32	20,960.0	460.95	243.43	–
2	150.37	18,400.1	430.95	213.56	12.3
3	157.16	20,086.6	446.77	229.34	5.8
4	160.77	19,727.5	446.74	229.29	5.8
5	148.18	18,144.6	427.35	210.07	13.7
6	147.16	18,534.0	428.39	211.20	13.2
7	158.57	19,486.7	444.79	227.52	6.5
8	154.16	19,421.6	439.46	222.21	8.7
9	148.92	18,189.6	428.72	211.40	13.2
10	150.15	18,352.4	430.34	213.02	12.5
11	146.49	17,832.0	424.71	207.61	14.7
12	149.71	18,308.7	428.40	211.10	13.3
13	151.41	19,198.5	437.40	220.06	9.6
14	150.53	19,013.3	435.44	218.25	10.3
15	143.50	18,077.1	423.73	206.54	15.2
16	145.93	17,944.5	424.81	207.61	14.7
17	149.92	18,771.9	433.22	216.05	11.3
18	144.77	18,504.4	427.23	210.00	13.7
19	139.44	17,925.5	419.83	202.55	16.8
20	139.50	17,995.3	420.08	202.84	16.7

[a]From existing conditions.

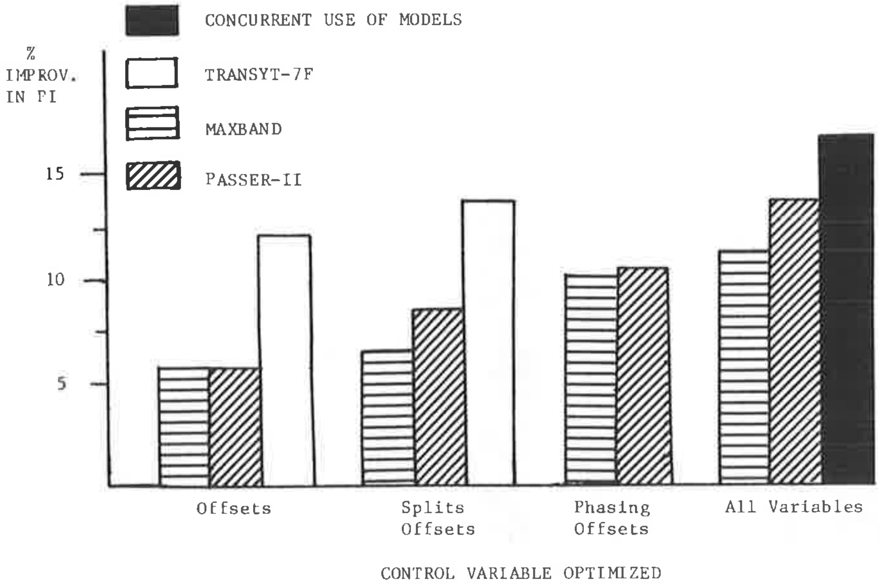

FIGURE 3 Optimization of phasing, splits, and offsets.

ditions, whereas the other models improved the system performance by about 6 percent. Offsets from MAXBAND and PASSER-II produced the same results, less than 1 percent difference in the MOEs. TRANSYT-7F offsets resulted in 5 percent fewer delays and stops compared with the offsets from the bandwidth models.

In optimizing splits and offsets, TRANSYT-7F timings again were better than those of the bandwidth models. TRANSYT-7F outperformed MAXBAND by about 7 percent in delays and stops and 4 percent in fuel consumption. TRANSYT-7F timings also resulted in 4 percent fewer delays, 7 percent fewer stops, and 3 percent less fuel compared with those of PASSER-II. PASSER-II timings had slightly better performance than those of MAXBAND, resulting in fewer delays by 3 percent (Runs 7 and 8). Improved starting values of either offsets or splits and offsets did not affect the final optimization with TRANSYT-7F. The difference in the MOEs was ±1.5, percent and the maximum improvement in the PI was only 1 percent (Runs 5 and 11). This is in agreement with the results obtained from the two-phase scenario (Experiment 1).

When the sequence of phases and offsets is optimized with the splits kept fixed, MAXBAND and PASSER-II had almost identical results in all the MOEs. Optimization of the sequence of phases led to significant improvements; both models improved the PI by 10 percent, which is considerably higher than the 6 percent improvement obtained from the optimization of offsets. The optimized phasing and offsets were then put to TRANSYT-7F for final optimization. The system performance was improved by about 1.5 percent over the TRANSYT-7F optimum solution from existing settings (Runs 5, 15, and 16).

When the splits are optimized with the phasing and offsets, PASSER-II timings were better than those of MAXBAND by about 3 percent in delay and 2 percent in stops and fuel. The PASSER-II settings had the same performance as those of TRANSYT-7F, and MAXBAND's solution was off the TRANSYT-7F optimal by 2.8 percent (Runs 5, 17, and 18). Although this is not a direct comparison because phasing in TRANSYT-7F was not optimized, it indicates that the bandwidth models can be effectively used for timing multiphase signals with different phasing alternatives. The use of the complete timing plan from either MAXBAND or PASSER-II as input to TRANSYT-7F for final optimization led to a further 3.5 percent improvement in the PI. The biggest improvement was a 6 percent reduction in delay; stops were reduced by 1 percent and fuel consumption by 1.7 percent (Runs 5, 19, and 20).

The analysis of the results from Experiment 2 showed that PASSER-II and MAXBAND are very effective in optimizing the sequence of phases and produce similar results when the splits are kept fixed. The use of either of these models to provide initial settings to TRANSYT-7F leads to modest improvements when the optimal phasing is input, and practically no additional improvement was obtained when phasing was kept fixed.

Experiment 3: Cycle Length Selection

Computer runs were performed to determine the optimum cycle length for the system with the three-phase scenario (Table 8). The results are summarized in Table 9. Under the existing phasing, the cycle search routine in TRANSYT-7F involved use of a cycle length of 75 sec as the best one after splits and offsets were optimized. Repeated TRANSYT-7F runs were also made for a range of cycles of 70 to 90 sec by using existing splits and offsets, and the results confirmed that 75 sec was the best cycle derived from the model. PASSER-II produced a cycle length of 80 sec and the optimal cycle from MAXBAND was 77 sec. The timings from the models improved the system performance by 8.5 to 14.7 percent. TRANSYT-7F was better than PASSER-II by 4 percent in delay, 8 percent in stops, and 3.5 percent in fuel consumption. TRANSYT-7F timings resulted in 5 percent fewer stops compared with the MAXBAND settings; total delay was the same. MAXBAND gave better results than PASSER-II.

When the phase sequences were optimized together with the other control variables, the best cycle length from PASSER-II was 85 sec and from MAXBAND 88 sec. PASSER-II timings were better than those of MAXBAND; delays were reduced by 4 percent, stops by 6 percent, and fuel by 2.8 percent (Runs 6 and 7). MAXBAND had a slightly better performance when the splits were kept fixed (Runs 5 and 6). The advantage of the bandwidth models in selecting the best phas-

TABLE 8 Design of Experiment 3: Cycle Length Selection—Three-Phase Scenario

Run No.	Control Variable Optimized	Source of Initial Settings				Final Optimization
		Cycle	Phasing	Splits	Offsets	
1[a]		Existing	Existing	Existing	Existing	
2	Cycle/	None	Existing	Default	Default	TRANSYT
3	Splits/	None	Existing	None	None	PASSER-II
4	Offsets	None	Existing	None	None	MAXBAND
5	All	None	None	None	None	MAXBAND
6	Variables	None	None	Existing	None	MAXBAND
7		None	None	None	None	PASSER-II
8		PASSER-II	PASSER-II	PASSER-II	PASSER-II	TRANSYT
9		MAXBAND	MAXBAND	MAXBAND	MAXBAND	TRANSYT
10		MAXBAND	MAXBAND	Existing	MAXBAND	TRANSYT

[a] Existing conditions.

TABLE 9 Results from Experiment 3: Cycle Length Selection

Run No.	Best Cycle Length (sec)	Measurse of Effectiveness				Improvement in PI[a] (%)
		Delay (vehicle-hr/hr)	Stops (stops/hr)	Fuel (gal/hr)	PI	
1	70	168.32	20,960.0	460.95	243.43	–
2	75	149.05	17,591.4	424.72	207.59	14.7
3	80	157.44	19,077.3	440.16	222.82	8.5
4	77	150.56	18,604.5	433.17	215.81	11.3
5	88	156.25	17,692.5	431.39	214.12	12.0
6	88	152.35	18,016.8	430.92	213.51	12.3
7	85	146.83	16,890.4	419.53	202.38	16.9
8	85	142.21	16,435.5	413.09	195.90	19.5
9	88	143.98	16,606.7	415.53	198.39	18.5
10	88	145.52	16,537.8	415.92	198.78	18.3

[a] From existing settings.

ing is again shown in this experiment. PASSER-II improved the PI by about 17 percent from the base conditions, whereas TRANSYT-7F improved the PI by about 15 percent with existing phasing. MAXBAND also improved system performance by 12.3 percent.

It can be seen from the results shown in Table 9 and Figure 4 that the best alternative for concurrent use of the programs was to input the cycle length and the other timings from PASSER-II as starting values to TRANSYT-7F. The PI was improved by about 6 percent compared with the TRANSYT-7F optimal solution with the 75-sec cycle and the existing phasing. Delays were reduced by 4.6 percent, stops 6.6 percent, and fuel by 2.7 percent. The PI was also improved by 4.5 percent by using the timings from MAXBAND as starting values to TRANSYT-7F. Total delay was reduced by 3 percent, stops by 5.6 percent, and fuel by 2 percent. The same results were obtained when splits were kept fixed and MAXBAND optimized the rest of the control variables. If it is assumed that a 2 percent difference in the TRANSYT7F results is attributed to the noise in the signal optimizer, then either one of the bandwidth models can be used to provide the initial timing plan for TRANSYT-7F optimization.

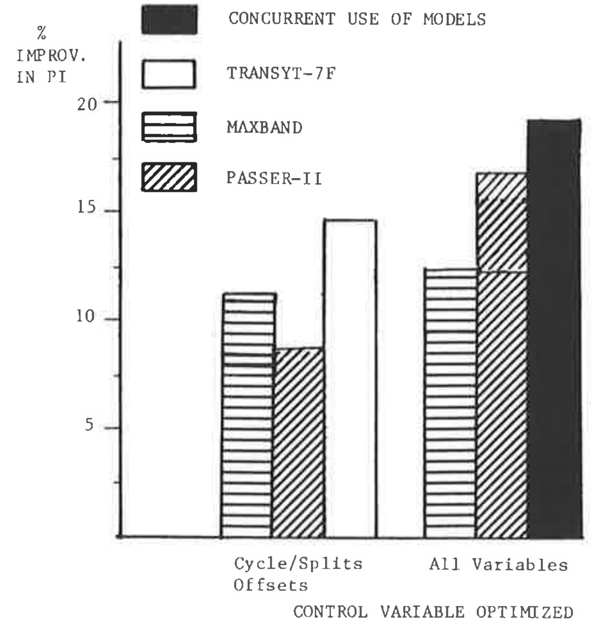

FIGURE 4 Cycle length selection—three-phase scenario.

DISCUSSION

The following comments and suggestions can be made with regard to improvements in the optimization capabilities and the practical use of the selected models:

1. The optimization algorithms of the bandwidth models should be modified to consider system measures, such as delays and stops. One option would be to consider the volume variations along individual links on the arterial instead of overall directional volumes for weighting the bands. Modeling of traffic could also be improved to consider the platoon characteristics of the traffic stream. Another option, currently being implemented in the new version of PASSER-II, is the adjustment of offsets for minimum delay subject to the bandwidth constraints.
2. The TRANSYT-7F model could be extended to "optimize" the sequence of phases. One procedure would be to automatically evaluate alternatives and select promising phasing for full optimization. Another option is to have a bandwidth program to optimize phasing as preprocessor to TRANSYT-7F in a single package.
3. PASSER-II and MAXBAND require considerably less effort in data processing and input coding and they are easier to use than TRANSYT-7F. Neither model, however, can evaluate the performance of the existing timing plan, nor do they provide estimates of the MOEs to quantify the benefits from the signal timing optimization. The practical applications of MAXBAND can be increased if additional output is provided for interpretation of the signal settings, for example, signal controller tables and time-space diagrams. Another improvement for PASSER-II would be the ability to optimize the timing of crossing arterials and triangular networks.
4. TRANSYT-7F is a powerful tool for a range of

applications but substantial effort is required to collect and code the data in the model. Interactive programs to facilitate the input coding and checking for coding errors would make the model much easier to use. These programs would be particularly useful because the model is now available on microcomputers and easily accessible to many users. Graphics packages to display the model results would also increase the application of the model. (Work in these areas is in progress at ITS.)

SUMMARY

The timings from MAXBAND and PASSER-II produced identical results in all the MOEs for all the combinations of the control variables optimized when the splits were kept fixed. PASSER-II showed a slightly better performance when the splits were optimized. Both models significantly improved the traffic performance from the existing settings, and they are particularly useful for timing multiphase arterial systems when the phase sequences are optimized.

The results indicated that the TRANSYT-7F model generated the most efficient timing plans for the arterial studied when splits, offsets, and cycle lengths were optimized. When the phase sequences also are optimized, the bandwidth models produced results comparable to those of TRANSYT-7F. Comparisons of TRANSYT-7F and other models should be interpreted with caution because of the use of TRANSYT-7F as the basic evaluation tool. However, the results from representative NETSIM runs confirmed the general pattern of results. Extensive use of the NETSIM model would require substantial effort because of the stochastic nature of the model and the need for several replications. Another limitation of the study is that one site is considered and the findings may vary when the models are applied on other arterials with different supply and demand characteristics. Further evaluation of these models to obtain more general results is planned at ITS.

The concurrent use of the optimization programs did not result in significant improvements for split and offset optimization under either the two- or three-phase scenario. Different initial settings of splits and offsets did not affect the TRANSYT-7F optimization process. There is a potential for improvements when the bandwidth models optimize the cycle length and phase sequence before the final optimization with TRANSYT-7F. This strategy led to a further improvement of about 5 percent from the TRANSYT-7F optimal settings for the arterial studied. The results also indicated that it is not significant which bandwidth program was used to provide the initial timing plan.

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Optimization of Left-Turn Phase Sequence on Signalized Arterials

S. L. COHEN and J. R. MEKEMSON

ABSTRACT

The traffic engineer has four variables available that can be adjusted to provide signal timing plans for signalized urban-suburban arterials. These are green phase time, offset, cycle length, and left-turn phase sequence. Up until recently, the last of these variables has received very little attention. In recent years, two signal optimization computer programs, MAXBAND (1) and PASSER-II (2), have been developed. Through use of these programs, the impact of changing left-turn phase sequence so as to maximize the amount of green bandwidth on a two-way signalized arterial with left-turn phases at some or all of the intersections can be explicitly considered. However, there has also been a tendency to utilize signal optimization programs that use vehicular delay as a measure of performance rather than bandwidth. Unfortunately, the delay-based programs, TRANSYT-7F (3), SIGOP-III (4), and SSTOP (5), cannot optimally select left-turn phase sequence. Thus, the objective of this study was to examine whether using a bandwidth-based program for the selection of left-turn phase sequence subsequently followed by delay-based programs to determine the final offsets generates signal timing plans with lower delay than either class of programs individually. Data from seven arterials of widely varying characteristics were available for this study. It was found that optimizing phase sequence can substantially improve the performance of MAXBAND, both in terms of increased bandwidth and decreased delay and stops. The use of phase sequence patterns optimized by MAXBAND in TRANSYT-7F has the potential for further improving signal timing plans produced by the latter program. However, use of phase sequence patterns optimized by MAXBAND in SIGOP-III apparently has the potential for producing signal timing plans with reduced performance.

The traffic engineer has four variables available that can be adjusted to improve the effectiveness of signal timing plans for signalized arterials. Three of them, green phase time, offset, and cycle length, are very familiar and can be calculated, more or less, by using various programs (1-5). The fourth variable, however, left-turn phase sequence, is less familiar as a signal timing variable; hence a detailed description of its application is in order. Take an arterial intersection with left-turn lanes or bays and left-turn phases on both arterial approaches. There are thus four possible combinations of the two left turns and two through phases (such as National Electric Manufacturers Association phases 1 and 5, and 2 and 6) (Figure 1). They are

1. Both left-turn lanes leading both through lanes (lead-lead);
2. Both left-turn lanes lagging both through lanes (lag-lag);
3. Inbound left-turn lane leading concurrently with inbound through lane; outbound left-turn lane lagging concurrently with outbound through lane (lead-lag); and
4. Outbound left-turn lane leading concurrently with outbound through lane; inbound left-turn lane lagging concurrently with inbound through lane (lag-lead).

The only extensive work that has been done on the effects of left-turn phase sequence has been performed by Texas. In particular, the FACTS (6) system was developed there. The FACTS system is a real-time arterial signal-control system that can implement signal turning plans, which are developed off-line by using the PASSER-II program in response to inputs from a surveillance system. In developing the plans, all four variables are used for optimization. In particular, each plan may have a different left-turn phase sequence and individual plans can be implemented on a cycle-by-cycle basis. The FACTS system has been installed and evaluated on the NASA-1 arterial south of Houston. Preliminary results appear promising (6).

SIGNAL TIMING PROGRAM CATEGORIES

Signal timing plans for signalized arterials in urban or suburban areas are developed by computing a set of values for each of the variables described previously. A number of computer programs are available that will optimize some of the variables. These programs can be divided into two general classes:

Class 1

Delay-based programs: These programs are characterized by a macroscopic traffic model that uses traffic flow, geometric, and signal timing inputs to estimate total delay and total stops. A gradient search optimization procedure is then used that adjusts signal parameters so as to minimize a weighted sum of stops and delay as estimated by the traffic model. Examples of such programs include TRANSYT-7F

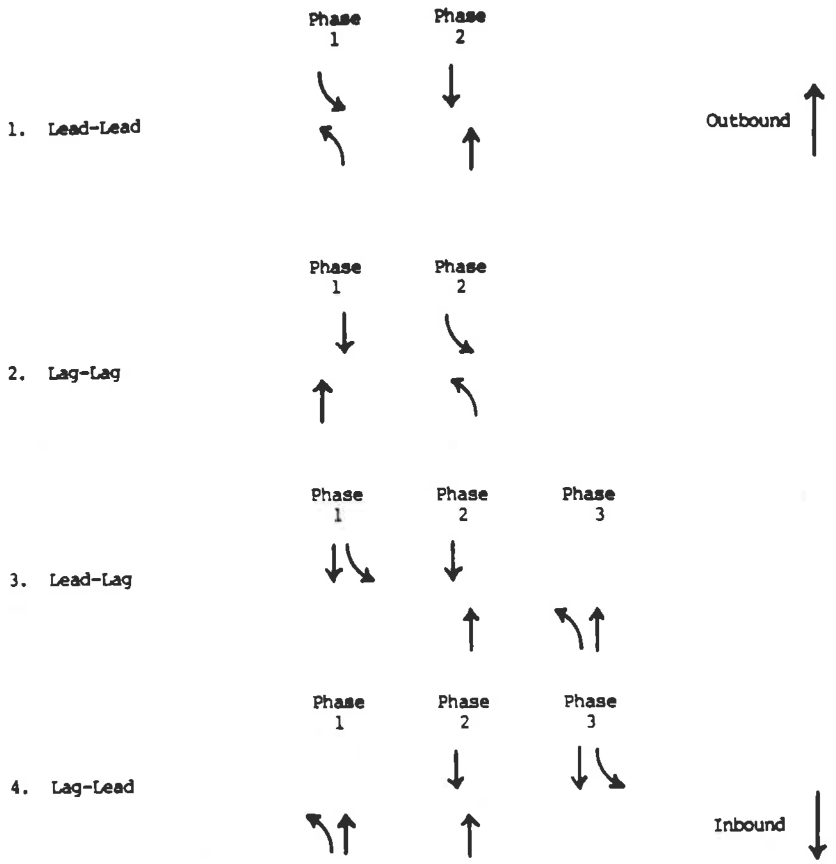

FIGURE 1 Allowable left-turn-through phase sequence combinations.

(3), SIGOP-III (4), and SSTOP (5). It should be noted that the weighed sum or delay and stops is called the Performance Index (PI) in TRANSYT-7F and Disutility (DIS) in SIGOP-III.

Class 2

Surrogate-based programs: These programs use a surrogate for the delay and stops performance measures that is much simpler to calculate, together with a more rigorous optimization procedure such as Mixed Integer Linear Programming (MILP). An example of such programs is MAXBAND (6), which uses bandwidth as the surrogate.

PROGRAM LIMITATIONS

One of the major limitations in using any of these programs is that none of them optimize all four variables. The delay-based programs optimize green phase time, offset, and cycle length; and the bandwidth programs optimize offset, cycle length, and phase sequence. The bandwidth programs sometimes have the ability to perform an initial green time allocation for each phase based on user-specified volumes and saturation flow rates. However, these computed green phase times generally remain fixed throughout the optimization procedure. PASSER-II, which has a three-step optimization process, recalculates green splits after the second step on the basis of a modified Webster's delay equation that attempts to account for platoon arrivals. One could, of course, do the same thing with MAXBAND by recomputing the splits after an optimization is complete and reoptimizing with the new splits. The logical approach to a universal program would be to extend the capability of one of them. However, adding phase sequence to the delay-based programs would involve combining a nonlinear gradient search technique with a combinatorial problem that appears computationally infeasible. This is because there are 4^n possible phase sequence combinations at n intersections with full left-turn phasing. For instance, Rogness (7) looked at the phase sequence optimization using a four-intersection arterial. This required a total of 256 (4^4) TRANSYT-7F runs to be made. On the other hand, MAXBAND's single measure of performance bandwidth provides no means for measuring and thus minimizing delay by adjusting green phase times. Green phase times are actually necessary constraints on the bandwidth optimization procedure because the maximum bandwidth occurs at zero green phase time for the cross street, which is unacceptable.

Another approach that has been suggested is to take one of the programs from each category and use them consecutively. Cohen (8) ran a number of scenarios by using data sets from two 8-intersection arterials, on the MAXBAND and TRANSYT-7F programs. He used the MAXBAND-computed green phase times together with optimized offsets and phase sequences as the starting solution for TRANSYT-7F. The latter program was then used to compute final offset and green phase times. By using the NETSIM model as the evaluation mechanism, it was shown that the resultant signal timing plans performed better than signal timing plans generated by either program alone for these two arterial networks.

In this work, findings that were based on a rather limited sample were greatly extended (7,8). The study focused on answering two questions: (a) What benefits relative to both increased bandwidths and reduced delay might be expected from optimizing the left-turn phase sequence? and (b) What is the response of delay-based programs when presented with an optimized left-turn phase sequence pattern determined by a maximum bandwidth program?

EXPERIMENTAL DESIGN

The experiments were restricted to the FHWA-supported programs TRANSYT-7F, SIGOP-III, and MAXBAND, using data sets from seven arterials, which are briefly described in Table 1. These data sets include a wide variety of geometric and traffic situations and therefore provide a good test for the effects of phase sequence optimization on arterials. The following comments apply to the conduct of the experiments:

1. The existing fixed-cycle length for each arterial was held fixed throughout all experiments. In addition, the values of green phase time computed in step a were also held fixed throughout subsequent steps b-f. This was done to isolate the effects of left-turn phase sequence optimization from the effects of green phase time and cycle-length optimization. If the cycle length and green phase times were allowed to vary, it would be impossible to determine whether phase sequence optimization alone is beneficial because of the confounding effects of the other variables.
2. A value of 4 was used as the stop weighting factor (seconds per stop) for both TRANSYT-7F's performance index (PI) and SIGOP-III's disutility (DIS). Because NETSIM was to be used as the evaluation mechanism for each of the three programs' generated signal timing plan, a NETSIM PI was constructed by using the same stop weighting factor, thus allowing a common measure across all programs.
3. The measures of effectiveness (MOEs) given for NETSIM and the values for PI given for TRANSYT-7F include both the arterial and side streets. The values for DIS given for SIGOP-III include only the arterial because there is no mechanism for including the entry link side street delays and stops in SIGOP-III. The green phase times in SIGOP-III are determined by the program that involves the use of the following mechanism: (a) The side street green phase times are initially adjusted so that the side street Volume 1 Capacity (V/C) ratio is equal to 85 percent or so that minimum green time is satisfied, whichever is larger; and (b) During optimization of DIS, more green time may be given to the side street if DIS is not thereby increased (i.e., if the SIGOP-III traffic model indicates there is unused green time on the main arterial phase.)
4. All calibration data (such as speeds, headways, etc.) required by the three optimization programs were obtained from the appropriate values used in NETSIM. NETSIM, in turn, was calibrated for each of the arterials by the user from whom we obtained the input decks. In most cases, however, the calibrations were limited to speeds and queue discharge headways.

The experiments were conducted according to the following steps for each arterial.

1. The MAXBAND program was run assuming that all left-turn phases were leading (i.e., the top diagram in Figure 1), which is standard practice in most jurisdictions at the present time. MAXBAND computes green phase times by using a modified Webster's approach and user-supplied volumes and capacities (actually saturation flow rates) that adjust for minimum green times if necessary. Green phase times are held fixed in succeeding steps to isolate the effects of left-turn phase sequence optimization as explained previously. (See Table 2 for before-and-after phase sequence optimization results.) The capacities were adjusted so as to agree with values obtained from NETSIM. This was done by noting intersection movements in the NETSIM run that were oversaturated and then adjusting downward the capacities for those movements used in MAXBAND. This results in the assignment of more green time to that movement by MAXBAND. This iterative procedure between MAXBAND and NETSIM was continued until there were no longer any oversaturated movements. MAXBAND then computes the offset pattern that produces the largest two-way bandwidth (inbound-outbound bandwidth ratio equal to 1). One of MAXBAND's user input options is the specification of a targeted inbound-outbound bandwidth ratio that could result in a higher level of performance. This option was not utilized for the previously stated purpose of isolating the effects of left-turn phase sequence optimization.
2. With green phase times fixed, TRANSYT-7F was exercised by using the default (zero offset) timing plan as the initial starting solution and capacities used in MAXBAND. TRANSYT-7F computed an offset pattern that produces the optimum PI. The default starting solution was used rather than the MAXBAND offset pattern solution to isolate the effect of left-turn phase sequence optimization from improved starting solutions. TRANSYT-7F's capability of improving the PI by adjusting all of the green phase times by using a gradient search technique was also not utilized in order to isolate the effects of left-turn phase sequence optimization.
3. With green times held fixed and by using the same mean queue discharge headway as was used in NETSIM, SIGOP-III was exercised to compute an offset pattern that minimizes DIS.
4. The three timing plans were then tested by using the NETSIM model as the evaluation tool. All simulation runs were for 30 min of simulation time. Further discussion on simulation procedures is presented in the following section.
5. MAXBAND was then run a second time to compute the offset and optimal left-turn phase sequence pattern, which produces the largest two-way bandwidth.

TABLE 1 Arterial Descriptions

Arterial	Signalized Intersections	Lanes	Optimized Left-Turn Phases	Progression Speed	Cycle Length	Signal Spacing (ft)	Location
Hawthorne Boulevard	13	8	12	45	90	560-2,600	Los Angeles, Calif.
University Boulevard	10	4	9	30	80	480-1,440	Provo, Utah
Nicholasville Road	12	4	10	35	80	520-2,160	Lexington, Ky.
North 33rd Street	9	4/6	7	35	75	353-1,605	Salt Lake City, Utah
Frederica Road	12	4	12	45	80	582-2,310	Owensboro, Ky.
Fannin Boulevard	15	6	12	35	80	300-1,900	Houston, Tex.
San Felipe Road	12	4	8	35	80	250-1,400	Houston, Tex.

TABLE 2 Before-After Phase Sequence Results for MAXBAND

	MAXBAND			NETSIM								
	Bandwidth (% of cycle, two-way band)			Delay (sec/vehicle)			Stops (stops/vehicle)			PI (vehicle-hr/hr)		
Arterial	Before	After	Change (%)	Before	After	Change (%)	Before	After	Change (%)	Before	After	Change (%)
Hawthorne	0.284	0.548	+93	80.16	64.94	-19	2.21	1.74	-21	263.4	212.7	-19
University	0.231	0.498	+116	42.40	35.39	-16	1.53	1.29	-16	98.0	82.4	-16
Nicholasville	0.368	0.480	+30	75.64	71.38	-5	2.27	2.00	-12	209.0	195.4	-7
North 33rd	0.092	0.268	+191	51.64	51.57	0	1.33	1.29	-3	242.3	247.0	-1
Frederica	0.470	0.718	+54	66.28	62.63	-6	2.10	1.95	-7	109.9	103.4	-6
Fannin	0.392	0.597	+52	63.59	54.28	-15	1.99	1.77	-11	176.0	151.0	-14
San Felipe	0.423	0.600	+42	51.44	49.60	-4	1.59	1.52	-4	170.3	163.8	-4

6. Steps 2-4 were repeated by using the optimized phase sequence patterns obtained in step 5.

GENERAL REMARKS

Before the results are discussed, two comments are necessary particularly with respect to the use of the NETSIM model.

1. The NETSIM model is a stochastic microscopic model that uses a sequence of randomly generated numbers to assign values to random variables such as speeds, queue discharge headways, start-up delays, left-turn gap acceptance, and so forth. For this reason, estimates of MOEs such as delay and stops will have a certain amount of variability in them depending on the particular sequence of random numbers used. Past experience with the model on undersaturated networks of size comparable with the ones used in this work has shown that this variability is approximately 3.5 percent. This means that when different timing plans are compared for the same network, a difference of 4 percent or less is probably not statistically significant. A review of the 15- and 30-min cumulative statistics for the seven arterials studied indicated that the network statistics were stable.
2. The traffic models used in TRANSYT-7F and SIGOP-III are macroscopic and deterministic and, by necessity, represent oversimplifications of traffic behavior in networks. Thus it can happen that apparent improvements predicted by them may not appear when a more detailed model such as NETSIM is used. This is not of any practical significance if one is looking at small discrepancies. In Table 3 for example, TRANSYT-7F predicted an improvement of 4 percent in PI for San Felipe Road, whereas NETSIM showed no improvement in delay and stops. It is not at all improbable that a 4 percent effect predicted by TRANSYT-7F could be washed out by those factors that were taken into account by NETSIM. On the other hand, evidence of large discrepancies indicates a potential problem with the macroscopic traffic model. For example, in Table 4 SIGOP-III predicted an improvement of 27 percent in DIS for University Boulevard, whereas NETSIM showed a decline of 19 percent. This indicates a very substantial difference between the behavior of traffic on the arterial as simulated by the two models.

INTRAMODAL RESULTS AND DISCUSSION

Tabulations of before-and-after phase sequence optimization results for each of the programs are given in Table 2 for MAXBAND, Table 3 for TRANSYT-7F, and Table 4 for SIGOP-III. Table 2 gives tabulations on the changes in bandwidth and NETSIM estimated delay, stops, and PI as a result of phase sequence optimization. Table 3 gives tabulations on the changes in NETSIM estimated delay, stops, and PI and TRANSYT-7F PI as a result of phase sequence optimization. Table 4 gives tabulations on the changes in NETSIM estimated delay, stops, and PI and SIGOP-III DIS. The results are summarized in the following paragraphs.

MAXBAND

1. As expected, optimizing phase sequence increased total two-way bandwidth because the MAXBAND formulation guarantees a global optimum (i.e., the largest possible bandwidth). Bandwidth increases ranged from 30 to 191 percent.
2. Arterial delay was reduced substantially in five of the seven arterials with reductions that ranged from 5 to 19 percent. The reduction in stops of from 7 to 21 percent was even more impressive, as might be expected, because the major effect of increasing bandwidth is to reduce the number of vehicles in the through platoon that have to stop.
3. Improvements in NETSIM PI ranged from 6 to 19 percent for the same five arterials.

TABLE 3 Before-After Phase Sequence Results for TRANSYT-7F

	TRANSYT-7F			NETSIM								
	PI (vehicle-hr/hr)			Delay (sec/vehicle)			Stops (stops/vehicle)			PI (vehicle-hr/hr)		
Arterial	Before	After	Change (%)	Before	After	Change (%)	Before	After	Change (%)	Before	After	Change (%)
Hawthorne	194.6	180.4	-7	71.89	64.04	-11	1.89	1.72	-9	234.7	210.4	-10
University	89.1	71.5	-20	38.93	36.12	-7	1.89	1.72	-8	90.4	84.0	-7
Nicholasville	167.2	161.4	-4	79.82	72.55	-9	2.28	2.07	-9	219.4	199.2	-9
North 33rd	226.2	219.0	-3	51.86	50.35	-3	1.36	1.29	-5	243.9	235.8	-3
Frederica	109.8	103.4	-6	66.46	62.96	-5	2.08	1.91	-8	109.7	103.9	-5
Fannin	159.7	152.8	-4	54.88	54.72	0	1.75	1.78	+2	152.0	152.2	0
San Felipe	207.6	202.6	-2	55.57	53.78	-3	1.55	1.60	+3	181.5	176.8	-3

TABLE 4 Before-After Phase Sequence Results for SIGOP-III

	SIGOP-III			NETSIM								
	DIS (sec/hr)			Delay (sec/vehicle)			Stops (stops/vehicle)			PI (vehicle-hr/hr)		
Arterial	Before	After	Change (%)	Before	After	Change (%)	Before	After	Change (%)	Before	After	Change (%)
Hawthorne	299,580	260,560	-13	78.57	84.12	+7	2.25	2.29	+2	259.6	275.7	+6
University	77,040	56,160	-27	41.45	49.44	+19	1.44	1.75	+21	95.4	114.0	+19
Nicholasville	223,020	207,248	-7	83.94	82.23	-2	2.38	2.30	-3	230.0	225.4	-2
North 33rd	210,936	201,288	-5	57.09	54.05	-5	1.43	1.36	-5	266.9	253.0	-5
Frederica	222,805	221,410	-1	65.47	69.01	+5	2.12	2.19	+3	108.6	114.6	+6
Fannin	158,558	15,630	-3	57.23	67.13	+17	1.89	2.01	+6	159.8	184.7	+16
San Felipe	160,335	166,185	+4	52.02	49.44	-5	1.55	1.50	-3	171.1	163.4	-4

TRANSYT-7F

1. Improvements in delay and stops were generally less significant than in the case of MAXBAND; NETSIM estimated that delay, stops, and PI were reduced on four out of the seven arterials.
2. Improvements ranging from 3 to 20 percent in the TRANSYT-7F PI were seen in all seven arterials.

SIGOP-III

Increases in delay and stops were seen in four of the seven arterials. This is particularly disturbing because improvements in DIS were predicted on the same four arterials by the SIGOP-III traffic model. The greatest difference was for University Boulevard where SIGOP-III estimated an improvement of 27 percent and NETSIM estimated a decline of 19 percent. The remaining three arterials had only minor improvements and only one of those (5 percent) was significant. On the basis of these results, it would appear that a serious problem exists in the SIGOP-III traffic model relative to the treatment of multiphase arterials. It would appear that further research (outside the scope of this study) is needed in this matter.

INTERMODAL RESULTS AND DISCUSSION

Before the results of the models are compared with each other, the following caveat is required: The MAXBAND runs use equal directional bandwidth weighting and equal allocations of slack green phase time. Here, slack green phase time is defined as the amount of arterial major phase green time that lies outside of the two-way bands. Preliminary studies have shown that adjustment of directional weighting can provide signal timing plans with lower delay. This is currently under further study in an FHWA contract. It has also been shown that adjustments of slack green in signal timing plans computed by bandwidth methods to accommodate queues may reduce delay (9). Therefore, it is likely that the MAXBAND results given below, especially for the the before-phase sequence optimization case where slack greens are larger, could be improved.

Given this caveat, the intermodal comparison shown in Table 5 is based on a TRANSYT-7F/SIGOP-III-like PI computed from NETSIM-generated delays and stops. It may be seen that the performance of all three models was fairly equivalent before optimization of the left-turn phase sequence, with TRANSYT-7F having a slightly better overall performance for the seven networks studied. MAXBAND and TRANSYT-7F again performed fairly equivalently after phase sequence optimization and performed substantially better than SIGOP-III in six of the seven arterials. For the San Felipe arterial, MAXBAND and SIGOP-III were equivalent and performed better than TRANSYT-7F.

CONCLUSIONS

From the results of this study, the following conclusions as applied to the seven arterials studied may be drawn:

1. Optimizing phase sequence can substantially improve the performance, both in terms of increased bandwidth and decreased delay and stops, of bandwidth optimization programs such as MAXBAND.
2. By using phase sequence patterns optimized by MAXBAND in TRANSYT-7F, the potential for improving signal timing plans produced by the latter program can be recognized.
3. By using phase sequence patterns optimized by MAXBAND in SIGOP-III, the potential for producing signal timing plans with reduced performance can be recognized.

FURTHER RESEARCH

Based on the findings of this paper and Rogness (7) and Cohen (8), the feasibility of extending the MAXBAND program to grid networks and integrating the resulting program with TRANSYT-7F into a single package can be assessed. The combined program would

TABLE 5 Comparison of Model Results Both Before and After Phase Sequence Optimization

	Before Phase Sequence Optimization (vehicle-hr/hr)			After Phase Sequence Optimization (vehicle-hr/hr)		
Arterial	MAXBAND	TRANSYT-7F	SIGOP-III	MAXBAND	TRANSYT-7F	SIGOP-III
Hawthorne	263.4	234.7	259.6	212.7	210.4	275.7
University	98.0	90.4	95.4	82.4	84.0	114.0
Nicholasville	209.0	219.4	230.0	195.4	199.2	225.4
North 33rd	242.3	243.9	266.9	241.0	235.8	253.0
Frederica	109.9	109.7	108.6	103.4	103.9	114.6
Fannin	176.0	152.0	159.8	151.0	152.2	184.7
San Felipe	170.3	181.5	171.1	163.8	176.8	163.4

have a common input stream and would have the capability of using the MAXBAND module to compute an initial timing plan and optimum phase sequence for the TRANSYT-7F module that could then fine-tune the offsets and green phase times for optimum PI.

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