TRANSPORTATION RESEARCH RECORD 906

Urban Traffic Systems

TRANSPORTATION RESEARCH BOARD

NATIONAL RESEARCH COUNCIL
NATIONAL ACADEMY OF SCIENCES
WASHINGTON, D.C. 1983

Transportation Research Record 906
Price $11.20
Edited for TRB by Mary McLaughlin

modes
1 highway transportation
2 public transit

subject areas
12 planning
54 operations and traffic control
55 traffic flow, capacity, and measurements

Library of Congress Cataloging in Publication Data
National Research Council. Transportation Research Board.
Urban traffic systems.

(Transportation research record; 906)
Reports for the TRB 62nd annual meeting.
1. Traffic engineering–Congresses. 2. Traffic engineering–United States–Congresses. I. National Research Council (U.S.). Transportation Research Board. II. Series.
TE7.H5 no. 906 [HE332] 380.5s 83-17454
ISBN 0-309-03520-1 [388.4'1312'0973] ISSN 0361-1981

Sponsorship of the Papers in This Transportation Research Record

GROUP 3–OPERATION AND MAINTENANCE OF TRANSPORTATION FACILITIES
Patricia F. Waller, University of North Carolina, chairman

Committee on Transportation System Management
John J. Roark, Rosewood Properties, chairman
Gary E. Maring, Federal Highway Administration, secretary
Paul N. Bay, Robert J. Benke, William D. Berg, Richard Dean Bowman, Alinda Burke, John P. Eicher, Ralph Gakenheimer, Joseph M. Goodman, David D. Grayson, David W. Gwynn, John R. Hamburg, Ronald J. Hartman, Charles A. Hedges, Harvey R. Joyner, Rodney W. Kelly, David R. Koski, David M. Levinsohn, Herbert S. Levinson, C. Howard McCann, William R. McGrath, James J. McLary, Rasin K. Mufti, Mark R. Norman, Chester F. Phillips, David C. Rhinard, Carlton C. Robinson, Dan A. Rosen, George J. Scheuernstuhl, Warren O. Somerfeld, Richard P. Steinmann, Edward F. Sullivan, Warren Travers, Herman Volk, Paul S. Wolf

Committee on Freeway Operations
Joseph M. McDermott, Illinois Department of Transportation, chairman
Elmer N. Burns, Ohio Department of Transportation, secretary
Patrick J. Athol, Keith E. Bushnell, Glen C. Carlson, E. Ryerson Case, Conrad L. Dudek, Walter M. Dunn, Jr., John W. Erdman, Herman E. Haenel, Richard W. King, Clifford L. Kurtzweg, Louis E. Lipp, Adolf D. May, Jr., William R. McCasland, Richard J. Murphy, David Rios Olivarez, Gary C. Price, David H. Roper, Dan A. Rosen, Ronald C. Sonntag, Asriel Taragin, Joseph Treiterer, Philip Zove

Committee on Traffic Signal Systems
Adolf D. May, Jr., University of California, chairman
David R. Koski, City of Minneapolis, secretary
William D. Berg, Kenneth G. Courage, Herman E. Haenel, H. Milton Heywood, E. Vinson Hoddinott, Jack L. Kay, Ken F. Kobetsky, Joseph K. Lam, Raymond S. Pusey, Philip J. Tarnoff, Roy L. Wilshire

David K. Witheford, Transportation Research Board staff

Sponsorship is indicated by a footnote at the end of each report. The organizational units, officers, and members are as of December 31, 1982.

Contents

Authors of the Papers in This Record

Arnold, E.D., Jr., Virginia Highway and Transportation Research Council, Box 3817, University Station, Charlottesville, VA 22903

Benevelli, David A., JHK and Associates, 97-45 Queens Boulevard, Rego Park, NY 11374

Caudill, Reggie J., Department of Civil Engineering, Princeton University, E-414 Engineering Quadrangle, Princeton, NJ 08544

Chin, Shih-Miao, Civil Engineering Department, Rensselaer Polytechnic Institute, Troy, NY 12181

Cohen, S.L., Federal Highway Administration, U.S. Department of Transportation, 400 Seventh Street, S.W., Washington, DC 20590

Eiger, Amir, Civil Engineering Department, Rensselaer Polytechnic Institute, Troy, NY 12181

Gartner, Nathan H., Department of Civil Engineering, University of Lowell, Lowell, MA 01854

Hurley, Jamie W., Jr., Department of Civil Engineering, Memphis State University, Memphis, TN 38152

Kabat, Richard J., Texas State Department of Highways and Public Transportation, P.O. Box 1386, Houston, TX 77251

Kuo, Nana M., Department of Civil Engineering, Princeton University, E-414 Engineering Quadrangle, Princeton, NJ 08544

Lantz, K.E., Jr., Virginia Highway and Transportation Research Council, Box 3817, University Station, Charlottesville, VA 22903

Levine, Steven Z., Texas State Department of Highways and Public Transportation, P.O. Box 1386, Houston, TX 77251

Lippman, Sandra S., Baltimore Regional Planning Council, 701 St. Paul Street, Baltimore, MD 21202

May, A.D., Institute of Transport Engineering, University of Leeds, Leeds LS2 9JT, England

Messer, Carroll J., Texas Transportation Institute, Texas A&M University, College Station, TX 77843

Powers, John C., Bureau of Transportation Systems Research, New Jersey Department of Transportation, 1035 Parkway Avenue, Trenton, NJ 08625

Radwan, A. Essam, Department of Civil Engineering, Virginia Polytechnic Institute and State University, Blacksburg, VA 24061

Reightler, Joel, Transportation Planning Division, Baltimore Regional Planning Council, 701 St. Paul Street, Baltimore, MD 21202

Rogness, Ramey O., Department of Civil Engineering, North Dakota State University, Fargo, ND 58105

Samdahl, Donald R., JHK and Associates, 4660 Kenmore Avenue, Alexandria, VA 22304

Simkowitz, Howard J., District of Columbia Department of Transportation, 415 12th Street, N.W., Washington, DC 20004

Southern, Valerie, District of Columbia Department of Transportation, 415 12th Street, N.W., Washington, DC 20004

Temple, John F., Florida Department of Transportation, Haydon Burns Building, 605 Suwannee Street, Tallahassee, FL 32301

Applying Transportation System Management Techniques to Downtown Washington, D.C.

HOWARD J. SIMKOWITZ AND VALERIE SOUTHERN

For a period of 18 months, the District of Columbia Department of Transportation has been actively involved in developing the transportation element of the Master Plan for Downtown Washington. The transportation element relies heavily on the transportation system management (TSM) philosophy and includes transit enhancement, ridesharing incentives, and pedestrian improvements that work together to create a better-functioning environment for all modes and for all activities vital to a successful downtown. In addition, it complements and is dependent on transportation actions occurring in other sections of the District. These include the growing Metrorail system, the parking enforcement program, and the neighborhood TSM program. An analysis was conducted to determine the transportation impacts of the proposed land use changes for the year 2000. This included an assessment of the Metrorail and road system capacities, parking levels needed to ensure mode-split objectives, and an identification of and a plan to reduce conflicts between pedestrians, automobiles, transit services, and delivery vehicles. This effort has produced a plan that is currently being implemented. Elements of the plan include a street classification system, pedestrian enhancements, streetscape design guidelines, sidewalk cafe legislation, public transit and ridesharing enhancement and promotion, a parking management program, and regulations covering the movement of goods.

For a period of 18 months, the District of Columbia Department of Transportation (DOT) has been actively involved in developing the transportation element of the Master Plan for Downtown Washington. The transportation element relies heavily on the transportation system management (TSM) philosophy and includes pedestrian improvements, transit enhancement, and ridesharing incentives that work together to create a better-functioning environment for all modes and activities vital to a successful downtown. In addition, it complements and is dependent on transportation actions occurring in other sections of the District. These include the growing Metrorail system, the parking enforcement program, and the neighborhood TSM program.

The goal of the transportation element of the downtown plan is to develop a balanced transportation system for the downtown and make optimal use of the road network, mass transit, and public space. This goal is being accomplished with the following objectives in mind:

1. Meet the transportation needs of all users of the downtown;
2. Reduce conflicts between competing uses for street space--pedestrian, transit, automobile, truck, and bicycle;
3. Promote traffic safety;
4. Enhance the pedestrian circulation network and offer maximum accommodation to walking in the downtown;
5. Ensure the attractive and functional design of public space;
6. Promote the use of ridesharing and transit for the journey to work;
7. Give priority to public transit and ensure that it is an attractive alternative;
8. Minimize the use of the automobile for travel within and into the downtown, especially during peak hours;
9. Provide a supply of long- and short-term parking that is consistent with the goals of the downtown plan;
10. Promote the efficient and convenient movement of goods and services within the downtown; and
11. Allow for the safe and utilitarian use of the bicycle within the downtown.

The first part of this paper describes downtown Washington and discusses current and projected land use and the transportation system. Next, the study methodology is outlined and the results are presented. The final portion of the paper outlines the TSM actions that are being taken in response to these findings.

DOWNTOWN CHARACTERISTICS

Project Area

Downtown Washington, D.C., is bounded by Pennsylvania Avenue on the south, M Street on the north, 15th Street on the west, and 2nd Street on the east (see Figure 1). Historically, the downtown had been the major retail and employment center for the District and for the region. Following a significant decline in activity and relative importance in the 1960s and 1970s, the downtown is poised for enormous economic revitalization within the next 10 years. This growth will be due to the following factors:

1. Direct access from the expanding Metrorail system, tying outlying geographic areas to the downtown's six Metrorail stations,
2. The recent opening of the 16 000-seat Washington Convention Center located within the project area,
3. The near completion of the Pennsylvania Avenue Development Program, and
4. A recent surge of private investment in development throughout the project area, which is reflected in the following data on expected increases in land use:

Land Use	Existing	Year 2000	Change (%)
Retail (ft^2 000 000s)	5.7	5.9	4
Office (ft^2 000 000s)	14.5	38.1	163
Apartments (ft^2 000 000s)	0.46	0.89	239
No. of hotel rooms	3250	11 010	204
No. of residential units	4080	12 410	93

Project Area Population

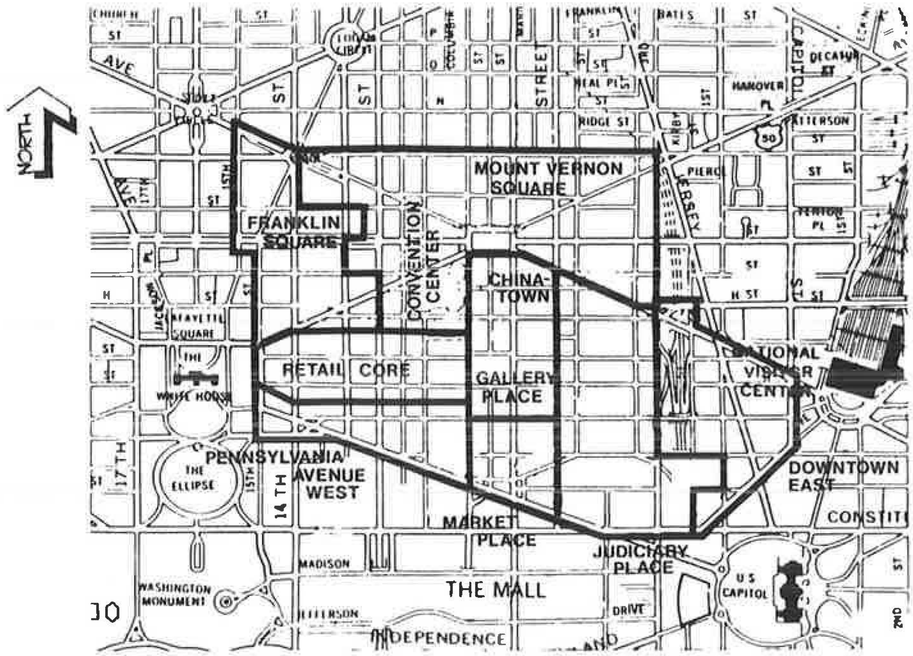
Work Force

An estimated 129 000 persons currently work in the downtown. By the year 2000, the downtown will employ nearly 224 000 persons, an increase of 74 percent. The greatest increases are anticipated in office employment, followed by the hotel and retail industries. Employment in the retail core of the downtown is expected to increase by 100 percent, from 16 000 today to 32 000 in the year 2000.

Shoppers

The downtown has traditionally contained the city's retail core. The Metrorail system has had a positive impact on the area by making it more competitive with the suburban shopping malls. Clientele

Figure 1. Downtown Washington, D.C.



has increased substantially since 1979. By the year 2000, the regional retail center is programmed to include five active department stores. Adjacent activity areas, such as Chinatown and Gallery Place, will extend shopper activity into the evening hours. Shopper volumes are expected to more than double during the downtown growth years.

Visitors

Approximately 17 million tourists, business travelers, and convention delegates visit Washington each year. The revitalization of the downtown retail center, the development of the Convention Center, and the completion of several hotels promise to bring many more tourists into downtown.

Residents

The downtown residential population has declined steadily over the past three decades. Today, fewer than 6000• persons live in the project area. However, 450 new housing units are now under construction and over 9000 units are planned.

Street System

The downtown street system is in the form of a grid with three major diagonal streets superimposed: Pennsylvania, Massachusetts, and New York Avenues. Blocks vary in length from 300 to 500 ft. The avenues are eight lanes wide. The letter and number streets, which form the grid, are between 45 and 70 ft wide and allow for four to six lanes. The curb lanes are typically reserved for parking, loading, and bus stopping and waiting areas during most hours of the day. On many streets, parking is prohibited during rush hours and some curb lanes are reserved for buses and vehicles turning right.

Sidewalks, measured from building line to curb, are approximately 20 ft on most grid streets. Sidewalk widths on Pennsylvania Avenue have recently been increased to 95 ft. The current sidewalk width on New York Avenue is 20 ft, but plans have been formulated to increase this to 32 ft. In all cases the actual width of sidewalk available for pedestrian circulation is less than the design width due to obstructions built or placed on the sidewalks.

Public Transit

The downtown public transportation system includes rapid rail, bus, and taxi.

Metrorail

The 101-mile Metrorail system, now about 39 percent completed, is focused on the downtown. Although only one-third of the regional system is in operation, Metrorail today carries almost one-half of all weekday transit trips and has become an important aspect of the regional transportation network.

There are six Metrorail stations with 13 entrances in the project area. The nearby Federal Triangle and Union Station stops also serve the downtown. According to a 1981 study conducted by the Washington Metropolitan Area Transit Authority (WMATA), 9 out of every 10 trips on the Metrorail system are to or from downtown destinations. Downtown ridership increased from 2.5 percent in 1977 to 34 percent in 1978 and to 44 percent in 1979.

The effect the Metrorail system has had on automobile travel to and from downtown Washington is noteworthy. Between 1977 and 1979, the total number of automobile trips entering downtown decreased by 30 800 and the total number of inbound automobile person travel trips decreased by 48 400. This represents a decrease of 7.6 and 8.3 percent in automobile and automobile person trips, respectively, into the downtown.

Bus System

Downtown is served by more than 90 bus lines extending to outlying areas within the District, Virginia, and Maryland. During the first quarter of 1982, the system carried 70 million riders, 70 percent of whom traveled to and from the downtown. The bus system provides both local and express service and transfer connections to the six downtown Metrorail stations.

METHODOLOGY AND ANALYSIS

Motivated by the large amount of growth anticipated

Table 1. Increase in afternoon peak-hour trips generated by year 2000 office development.

		Increase in Trips			
		60 Percent Peak-Hour Factor		50 Percent Peak-Hour Factor	
Mode Split[a] (%)	Automobile Occupancy (persons/ vehicle)	Automobile	Transit	Automobile	Transit
40/53/7	1.5	13 840	27 510	11 530	22 920
	1.7	12 210	27 510	10 180	22 920
	2.0	10 380	27 510	8 650	22 920
30/63/7	1.5	10 380	32 700	8 650	27 250
	1.7	9 160	32 700	7 630	27 250
	2.0	7 780	32 700	6 490	27 250
20/73/7	1.5	6 920	37 890	5 770	31 570
	1.7	6 110	37 890	5 090	31 570
	2.0	5 190	37 890	4 325	31 570

[a]Automobile/transit/walk.

in the downtown by the year 2000, the District of Columbia DOT conducted an analysis both to estimate the impact of this growth on the transportation system and to determine the limits of growth that would be possible, given the goals of the DOT and the constraints of the transportation system both in the downtown and citywide. The analysis addressed the following questions:

1. How can conflicts between pedestrians, vehicles, and transit be reduced, and how can an attractive and safe pedestrian environment be created?
2. What is the capacity of the Metrorail system (stations and trains), and what level of service can it be expected to provide?
3. What is the ability of the major arterials and bridges that serve the downtown to accommodate increased vehicle traffic?
4. What represents an appropriate parking supply, and do commuter and short-term parkers have conflicting needs?

The analysis assumed that the full 101-mile Metro system would be operating by the year 2000. It was also assumed that the road network would be fixed and there would be no future increases in capacity. Residential streets would not be used to accommodate any overflow from the arterial network. Recent actions taken by the DOT support this policy. Thirteenth Street, N.W., is no longer one-way during rush hours; the center reversible lanes on Reno Road, N.W., and Sixteenth Street, N.W., have been eliminated; and a study is being undertaken to determine the feasibility of changing Fifteenth Street, N.W., from one-way to two-way operation. All four streets are residential in nature.

Travel demand was estimated for the year 2000 based on a level of development that will completely fill the downtown building envelope. Peak-period trips will increase by 80 000, which is nearly a 100 percent increase over current volumes.

Scenarios assuming various mode splits, automobile occupancies, and peaking characteristics were tested to determine impacts. The "do-nothing" case assumed a 40 percent mode split, an automobile occupancy of 1.5 persons/car, and a 60 percent peak-hour factor. A more optimistic scenario assumed an effective TSM program that would result in a 30 percent automobile mode share, an automobile occupancy of 1.7 persons/car, and a 50 percent peak-hour factor. Under this scenario there would be 45 percent fewer vehicle trips to the downtown than if trip characteristics were to remain the same. Table 1 summarizes the travel demands under the various scenarios.

Pedestrian Circulation Analysis

The following activities were performed to determine pedestrian circulation conditions and needs in the downtown:

1. Inventory--Twelve-hour weekday pedestrian volume counts taken at 46 downtown locations;
2. Safety evaluation--A review of annual safety statistics, police accident records, and locations of pedestrian-vehicle conflicts in the downtown; and
3. Level-of-service analysis--A review of peak pedestrian flows and sidewalk and crosswalk capacities over time.

Inventory

Walking is the preferred mode in the retail core. More than 147 000 pedestrians were counted on 15 selected streets during one 12-h weekday period. This pedestrian volume is equivalent to the work force within 183 downtown office buildings or, put another way, the maximum capacity of 12 Convention Center events. The six retail core streets listed in the following table carry 45 percent of weekday pedestrian volumes:

	No. of Pedestrians		
Location	Midday Peak	Evening Peak	12-h Total
13th Street between F and G	3810	1 880	18 100
F Street between 12th and 13th	3080	1 680	16 300
F Street between 9th and 10th	2230	1 460	13 892
G Street between 13th and 14th	2190	1 750	13 400
11th Street between F and G	1570	1 860	13 100
F Street between 14th and 15th	1980	1 350	6 600
Total	9980	14 860	81 392

On these streets, the maximum flow was found to occur between 12:00 noon and 1:00 p.m. Twenty-one percent of the total 12-h flow is within this period. Pedestrian and vehicle volumes are compared below (the data are taken from a field study by JHK and Associates):

Location	No. of Vehicles	No. of Pedestrians	Ratio
13th Street between F and G	1200	1880	1.6
F Street between 12th and 13th	500	1680	3.4
F Street between 9th and 10th	500	1460	3.0
G Street between 13th and 14th	450	1750	3.9
11th Street between F and G	1100	1860	1.7
F Street between 14th and 15th	280	1350	4.8

These data indicate that pedestrian volumes exceed vehicle volumes by as much as 75 percent during the evening peak period (3:00-6:30 p.m.).

The Gallery Place and Metro Center Metrorail stations are major generators of pedestrian travel. Figure 2 indicates that 91 percent (1773 users) walk to Gallery Place in the evening peak. Only 5 percent arrive by bus and 1 percent by automobile. At Metro Center, 87 percent (6863 users) access the station via the walk mode, 6 percent arrive by bus, and only 1 percent by automobile. Land is expected to develop rapidly in the retail core by 1985. As a result, walking trips to Metro Center are projected to increase by 59 percent and to Gallery Place by 52 percent. By the year 2000, when the downtown is fully developed, pedestrian access is expected to increase by 200 percent.

Less pedestrian activity was recorded in other areas of downtown. During one 12-h weekday period, 97 000 pedestrians were counted at 31 locations. This volume is only 32 percent of that found on streets in the retail district.

Safety Evaluation

In 1980 there were more pedestrian accidents in the downtown than in other parts of the city. Of total accidents, 17 percent or 231 occurred in the downtown. Two pedestrian deaths were also recorded. Pedestrian accidents occurred most frequently at midblock locations (52 percent) and, to a lesser degree, at street intersections in crosswalks (41 percent).

Level-of-Service Analysis

A pedestrian level-of-service analysis was conducted based on work by Fruin (1) in which he defines six categories of pedestrian service. These range from unimpeded flow (level of service A) to jammed flow (level of service F). According to Fruin, the desirable pedestrian environment (level of service A) allows sufficient space to choose independently a relaxed walk speed, to bypass slower pedestrians, and to avoid conflicts with oncoming or crossing pedestrians. The following variables determine desirability: the area the pedestrian occupies, effective sidewalk width, queuing conditions, walk speed, pedestrian headways, and the number (or volume) of pedestrians within a given area.

By using the above variables, sidewalk level of service (s) was computed as

$$s = p/tw \tag{1}$$

where

p = number of pedestrians,
t = time interval, and
w = effective sidewalk width.

Crosswalk holding area capacity (h) was computed as follows:

$$h = (pt_1/t_2 l)q \tag{2}$$

where

t_1 = wait time,
t_2 = time interval,
l = traffic light cycle length, and
q = queuing space per pedestrian.

Last, crosswalk level of service (c) was computed by using the following values:

$$c = p(1 - t)/gw \tag{3}$$

where

t = reaction time,
g = pedestrian crossing time, and
w = crosswalk width.

As Table 2 indicates, the equations produced acceptable pedestrian service levels in 1981 and design year 2000 when successful public space and sidewalk management programs were assumed. Analysis indicated that service levels would decrease significantly to unacceptable levels if these programs were not implemented.

A separate analysis was conducted to determine pedestrian conditions at the Washington Convention Center. The facility, situated in the center of

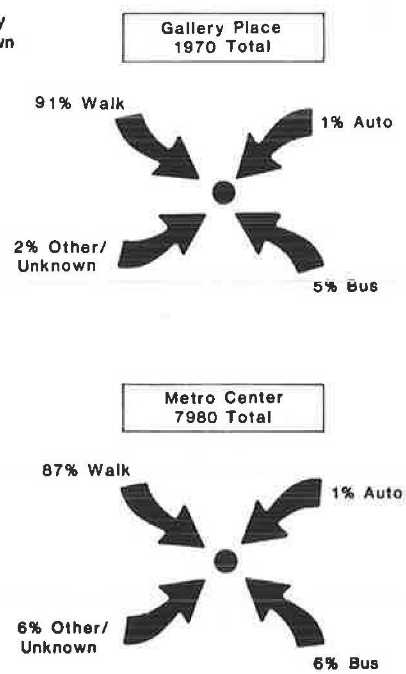


Figure 2. Metrorail access by mode at two major downtown stations: afternoon peak, spring 1981.

Table 2. Results of level-of-service analysis for retail core: 1981 and 2000 pedestrian conditions.

	Sidewalk Level of Service			Crosswalk Hold Area Capacity			Crosswalk Level of Service		
		2000			2000			2000	
Location	1981	No Public Space Management	Public Space Management	1981	No Public Space Management	Public Space Management	1981	No Public Space Management	Public Space Management
11th and G	A	C	A	+	-	+	A	D	A/B
11th and F	A	C/D	A	+	-	*	A	D	A/B
12th and G	A	C	A	+	•	+	A	D	A/B
12th and F	A	D	A	+	-	-	A	F	C
13th and G	A	F	A	+	-	+	A	D/E	B
13th and F	A	D	A	+	-	+	A	D	A/B

Note: + = adequate, - = not adequate, and • = moderately adequate.

Table 3. Afternoon peak level-of-service analysis for selected intersections.

	Level of Service				
		1990		2000	
Intersection	1981	A	B	A	B
4th Street and New York Avenue	A	D	C	E	D
6th and E Streets	A	A	A	A	A
6th Street and New York Avenue	C	F	E	F	F
7th Street and Pennsylvania Avenue	B	F	E	F	D
7th and H Streets	B	D	D	E	C
9th Street and Pennsylvania Avenue	E	F	F	F	F
9th and H Streets	C	D	C	E	D
9th and L Streets	B	D	C	F	D
11th and H Streets	A	C	B	D	C
12th and G Streets	A	E	C	F	D
13th Street and Massachusetts Avenue	B	F	E	F	F
14th Street and Pennsylvania Avenue	D/E	F	F	F	F
14th Street and New York Avenue	B/C	E	C	F	D

Notes: A = transportation conditions including 40 percent automobile mode share, 1.5-person automobile occupancy, and 60 percent peak-hour factor; B = TSM actions resulting in conditions of 30 percent automobile mode share, 1.7-person automobile occupancy, and 50 percent peak-hour factor.
Volumes are from manual "uncontrolled" assignment. Balancing of traffic among roadways could result in an improved level of service at particular intersections.

downtown, is expected to generate 10 000 pedestrian trips in either midday or evening peak periods, beginning in 1983. The analysis found that pedestrian conditions at the center will be close to if not intolerable during exiting times. System breakdown will be most apparent within at-grade crosswalk facilities. To safely accommodate peak pedestrian traffic, it will be necessary to "spread the peak," ensuring even distribution of traffic through designated egresses over a 20-min period, at minimum.

The pedestrian level-of-service analysis has clearly shown that pedestrian design standards are needed in the downtown to minimize the negative impacts of growth on the pedestrian network. These are discussed later in this paper.

Metro System Capacity

An analysis was performed to determine whether the Metro system will be able to accommodate the ridership levels projected for the year 2000. Both train and station capacities were evaluated.

Trains were assumed to consist of eight cars, each capable of carrying 200 persons, for a total capacity of 1600 persons/train. Escalator capacity was set at 115 persons/min and fare gate capacity at 25 persons/min. The number of escalators and fare gates represents the full system design. Fare gates were assigned an entry or exit direction proportional to demand.

The computer model for determining station capacity calculates the number of seconds of wait experienced by the last passenger to leave the station following each train arrival during the morning peak hour. The model also computes the number of escalators required to clear the train platform within 2 min, regardless of train headway.

By 1986, transit use at the two Metro stations in the retail core will more than double. By the year 2000, volumes will have nearly tripled. Both Metro station capacity and train capacity were found to be sufficient to handle the projected number of commuters under the full-built scenario for the downtown, even when a 30 percent automobile mode split was assumed. However, this capacity is contingent on the ability of Metro to provide eight-car trains traveling on 2-min headways during the rush hour and stations being built to their design capacity. Near-perfect reliability will be required since little slack exists in the system. For example, a train that is 4 min late will increase passenger exiting time at one of the downtown stations by 3 min. Trains on certain lines would not be able to accommodate all passengers trying to board at stations near the periphery of the downtown during the afternoon peak period if headways are longer than 3 min. This commitment to the Metro system becomes all the more imperative when it is realized that a very high transit mode share is necessary to avoid intolerable congestion on the street network.

Road System Level of Service

Level-of-service analyses were performed for 13 intersections in and around the downtown. The methodology followed was the critical-lane-volume technique taken from Transportation Research Circular 212 (2).

Most of the intersections were found to be operating without considerable delay during the peak periods (see Table 3). However, committed development will cause traffic volumes to increase from 50 to 100 percent by 1986, which will use up most of the existing capacity in the heart of the downtown. By the year 2000, 11 of the 13 intersections will be operating at unsatisfactory levels of service (E or F) under the "do-nothing" scenario. If this is permitted to happen, it could have severe implications for the attractiveness of the downtown as a work and shopping location. A successful TSM program would result in only 4 of these intersections operating at level of service E or F.

Parking Supply and Demand

A parking analysis was conducted to determine the amount of parking that is consistent with the modal split and automobile occupancy goals that have been established. An inventory of the existing on-street and off-street parking supply in the downtown yielded a supply of 25 000 spaces. The number of parking spaces that will be lost due to new development was subtracted from the supply. By the year 2000, only 16 000 of the current spaces will remain. From this figure it was then possible to calculate the appropriate amount of new parking.

The parking demand ratio (PDR) was calculated for each land use category. Mode split and automobile occupancy figures are based on goals set for the year 2000. Parameters such as average density of employees and shoppers are based on current figures.

In the case of office development, the following formula was used to compute the number of parking spaces required to meet the demand of employees in each 1000 ft² of development:

$$\mathrm{PDR(office)} = (A_1/A_2)E_1E_2 + V \tag{4}$$

where

A_1 = automobile mode share,
A_2 = automobile occupancy,
E_1 = persons/1000 ft² of office space,
E_2 = adjustment factor for employee absenteeism, and
V = visitor parking.

The equation was solved for a 30 percent mode split, 1.7 persons/car, 4 persons/1000 ft² of office space, a 15 percent absenteeism rate, and 10 percent visitor parking. The result was one parking space for each 1400 ft² of office development, which is close to the one space for each 1250 ft² currently being provided.

A similar formula was developed for retail trips:

$$\mathrm{PDR(retail)} = T_1T_2(A_1/A_2)F \tag{5}$$

where

T_1 = trips generated/1000 ft² of retail space,
T_2 = percent of shopper trips, and
F = shopper peaking factor.

The equation was solved for a 7 percent automobile mode share, 1.8 persons/car, 35 trips/1000 ft² of retail space, 90 percent shopping trips, and a peaking factor of 0.25. This resulted in one parking space for each 3250 ft² of retail space. No figures for the amount of retail parking being supplied for new developments were available for comparison. However, 2900 on-street spaces are designated for short-term parking, and most parking garages have been found to have at least a 10 percent vacancy rate.

The PDR for hotel rooms was calculated by using the following formula:

$$\mathrm{PDR(hotel)} = (A_1/A_2)R \qquad (6)$$

where R is room occupancy.

Assuming an automobile mode share of 20 percent (not including taxi trips), an automobile occupancy of 1.6 persons/vehicle, and an average room occupancy of 2.2 persons results in a PDR of one space for each 3.6 rooms. This figure is very close to current zoning requirements.

The residential parking requirement was set to reflect the current zoning requirement in the downtown: one space for every two condominiums and one space for every three apartments.

Based on the land use projected for the year 2000 (Table 1), 28 000 parking spaces will be required in the downtown. Current development practices imply that 15 000 new spaces will be constructed in the downtown, which is about 4000 more than the number required for the mode split and automobile occupancy goals that have been set.

DOWNTOWN TSM PROGRAM

The District of Columbia DOT has taken several actions and is developing additional programs to respond to the goals of the downtown plan and the findings of the analysis cited in the previous section of this paper. A "Downtown TSM Notebook" has been prepared that brings together these policies and programs in one document. The notebook will be distributed widely to developers, building owners, and employers. It will represent an important component in the District of Columbia DOT's outreach effort to the private sector. The following topics are included: goals, objectives, and policies; pedestrian program; street classification system; streetscape guidelines; sidewalk cafe legislation; public transit; ridesharing; parking management; and goods movement.

The pedestrian program has been developed to meet goals in the areas of physical improvements, design improvements, and public and private management. The downtown street classification plan identifies streets with a pedestrian emphasis and their operational requirements. The streetscape design review process sets the standards for the design and allocation of elements in the public space to improve the pedestrian environment. The sidewalk cafe legislation has been written to preserve pedestrian clear space and provide an attractive and comfortable pedestrian environment. The transit program attempts to reduce conflicts between transit patrons and pedestrians through improvements in the location of bus stops and the use of space around Metro stations. The parking management and ridesharing programs have as one of their goals a reduction in the number of vehicles entering the downtown. Finally, one of the goals of the goods movement program is to reduce conflicts between pedestrians and delivery vehicles.

The remainder of this paper discusses these topics.

Pedestrian Program

A comprehensive pedestrian program has been developed that will meet the following objectives:

1. Physical improvements--(a) Provide a pedestrian network accessing the entire downtown, (b) provide sufficient space for pedestrian circulation by regulating the location, type, and design of all sidewalk "furniture" (e.g., trees, benches, vending machines, signs, and vaults), (c) install curb ramps at all pedestrian crossing locations (ramp slopes should not be greater than 1 in/ft or exceed a 5 percent grade), (d) provide shelder, sun protection, and security at major pedestrian locations, (e) provide traffic signals timed for pedestrian rather than vehicle traffic, where appropriate, and (f) encourage consolidated freight deliveries at times least disruptive to pedestrian movement;
2. Design improvements--(a) Develop streetscape guidelines that provide clear technical standards for use of public space, (b) beautify public space by landscaping and providing trees, and (c) ensure attractive, well-designed pedestrian amenities, seating, and standing areas; and
3. Public and private management--(a) Promote well-designed, safe, and well-maintained public space amenities and activities within special pedestrian areas, (b) ensure security, and (c) coordinate street activities such as festivals, sales, art programs, and commercial street fairs.

Downtown Street Classification Plan

Underlying many of the transportation objectives is the concept of a street classification plan. The downtown street network provides mobility and access for automobiles, trucks, surface transit, and pedestrians. Its proper functioning is also a key determinant of the quality of life experienced by persons in the downtown. Since the downtown is slated to experience major growth and since it is only possible to make minor physical modifications to the downtown streets, the existing system must be carefully managed so that it can best respond to these needs. The downtown street classification policy identifies how each street should function and how conflicts between the different uses of the street space can be resolved.

The street classification policy defines the role each downtown street plays in the provision of access and circulation. To this end, city streets are grouped in three basic hierarchical classifications: traffic streets, bus streets, and streets with a pedestrian emphasis. Each classification is further divided based on its role in the overall street system. Figures 3-5 show maps displaying the classification system and explain the functional purpose, traffic operations, transit operations, access, and pedestrian treatment of the streets shown. In several instances, because streets serve two purposes they have been given a dual classification.

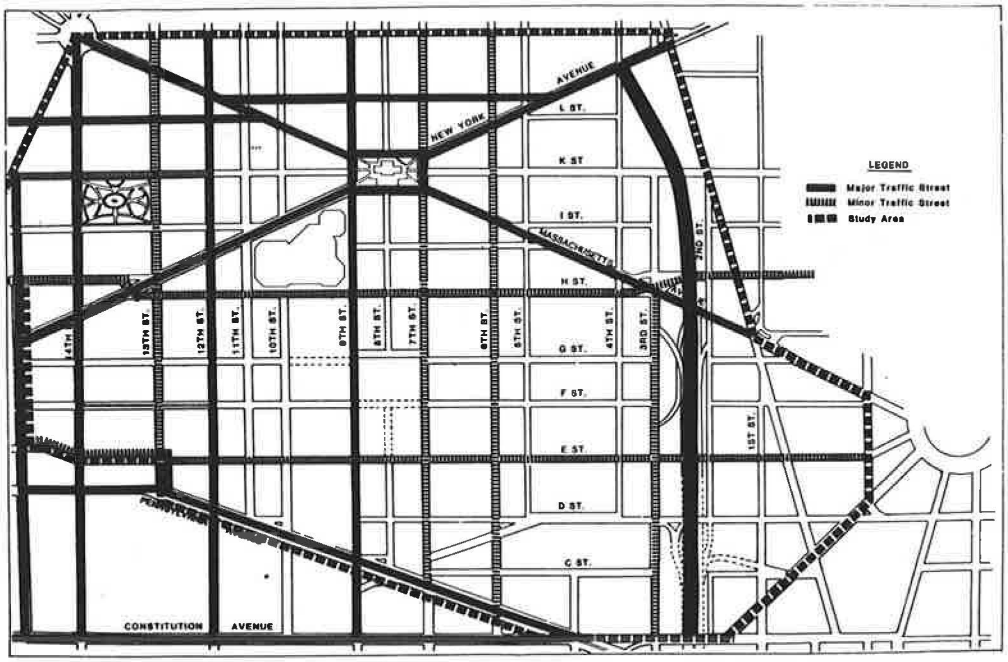
Streetscape Design Review Process

As part of the building and remodeling process, developers are responsible for restoring sidewalk areas. Increasingly, they have begun to install their own sidewalk improvements. The City realized that guidance and coordination were needed if these improvements were, in fact, to represent an upgrading of the quality of public space design. Although the City has construction, design, and materials specifications, its role in approving elements proposed for use in public space as part of the building permit process was limited, focusing primarily on safety concerns and the needs of utilities.

Recognizing the opportunity that the redevelopment of the downtown presented, the DOT and the Office of Planning and Development (OPD) produced a draft downtown streetscape notebook in the fall of 1981. It included standards for the design and location of building and utility vaults, paving materials, trees and landscaping, curb cuts and driveways, and street lights. One of the most significant elements was the requirement that developers pay for the installation and maintenance of the landscaping and sidewalk paving elements.

Within the downtown, developers of new or rehabilitation projects are now required to submit a streetscape plan for review and approval by the Streetscape Review Committee. The process is a two-

Figure 3. Proposed street functional classification plan showing major, minor, and local traffic streets.



Major Traffic Street

- prime carrier of traffic
- special effort to maintain efficient flow
- transit vehicles permitted
- curb cuts permitted
- special effort to ensure safe pedestrian crossings

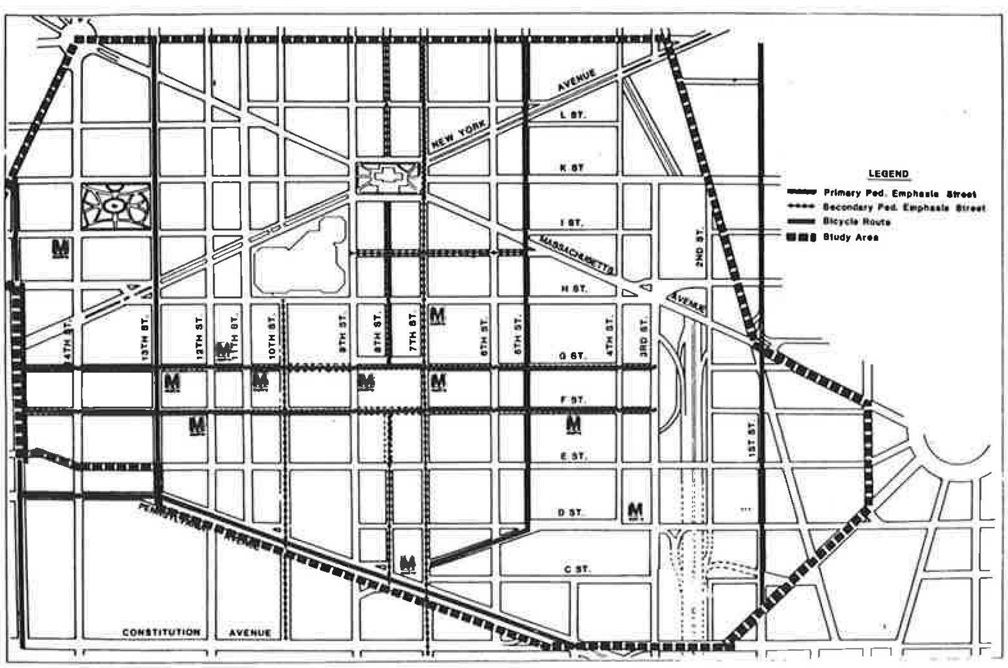
Minor Traffic Street

- distribution function
- efforts made to maintain efficient flow
- transit vehicles permitted
- preferred location for curb cuts
- ensure safe pedestrian crossings

Local Traffic Street

- serve abutting street
- ensure street operates safely
- transit vehicles permitted
- preferred location for curb cuts
- enhance pedestrian environment

Figure 4. Proposed street functional classification plan showing streets with major or minor pedestrian emphasis and bicycle streets.



Major Pedestrian Emphasis Street

- prime street for pedestrian activity
- minimize auto traffic
- transit vehicles permitted
- curb cuts prohibited unless no reasonable alternative
- pedestrian movement and amenity is prime concern

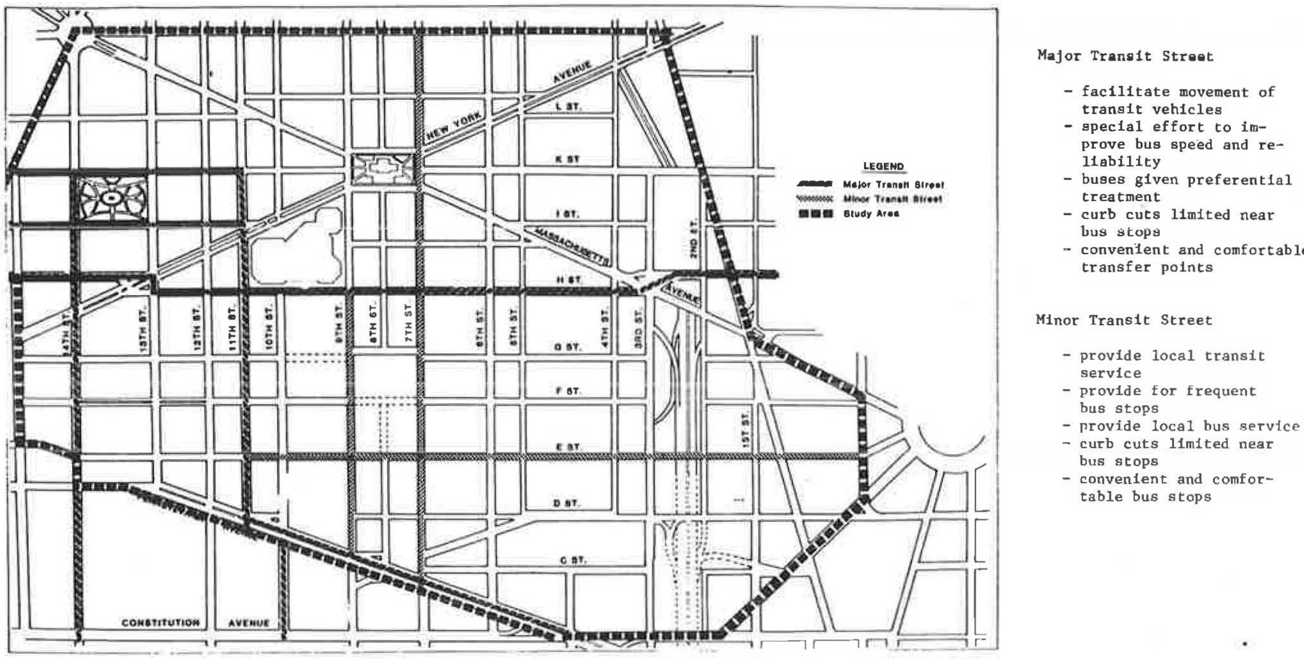
Minor Pedestrian Emphasis Street

- emphasis on pedestrian movement
- discourage auto traffic
- transit vehicles permitted
- curb cuts prohibited unless no reasonable alternative
- pedestrian movement and amenity is prime concern

Bicycle Street

- provide safe route for bicycles
- special effort made to increase safety
- transit vehicles permitted
- limited curb cuts
- enhance pedestrian environment

Figure 5. Proposed street functional classification plan showing major and minor transit streets.



step one, requiring the submission of a streetscape plan at the beginning of the building process, before underground permit approval is given, and at the end, before paving and other public space permits are issued. Although the review process does not replace any public space permit requirements, it provides a coordinated, one-step review by the city DOT of elements in the public space.

Plans for more than 28 projects have formally been submitted and at least a dozen more developers have met with staff for guidance. Although there have been minor problems of coordination in establishing the process, developers have, for the most part, been supportive and have voluntarily followed the guidelines. However, all developers are unlikely to meet the standards unless required to do so. Passage of authorizing legislation is needed to ensure the success of the program.

Sidewalk Cafe Legislation

The District of Columbia DOT has worked closely with the City Council and citizen groups to develop sidewalk cafe legislation. The purpose of this legislation is to preserve the pedestrian clear space and provide an attractive and comfortable pedestrian environment. Many of the existing sidewalk cafes have been constructed so that they make pedestrian circulation difficult. Others have erected "permanent" walls that create a de facto advance in the building line and have negative effects on the pedestrian environment.

The legislation specifies that the cafes may not be enclosed between May 15 and October 15 and may not project more than 20 ft from the building line or occupy more than 60 percent of available surface space. All existing enclosed sidewalk cafes must comply with these standards within 18 months of the effective date of the act.

Public Transit

The analysis has shown that many of the arterial roadways leading to the downtown are congested today, and downtown development committed for 1985-1986 will use up much of the existing capacity on the downtown streets. As a result, a policy that gives priority to the use and development of public transit service to the downtown has been adopted.

To ensure the city's return on its Metrorail investment, increased emphasis on both the use and revenue-generating potential of the system is necessary. As stated earlier, the system must be operating at its design capacity of 2-min headways and eight-car trains if it is to accommodate year-2000 demand. The city DOT encourages developers to construct mixed-use projects in order to balance transit demand over the day and evening hours. In this way, the system will be used during peak and nonpeak travel periods.

Proposed changes to the zoning regulations permit parking requirements for nonresidential structures within a radius of 800 ft of a Metrorail station to be reduced by 25 percent. In addition, the Board of Zoning Adjustment will be able to reduce or eliminate the amount of required parking spaces for nonresidential buildings if the building is provided with a direct connection to a Metrorail station or there is a high level of public transportation service in the area.

The current road network in the downtown offers little in the way of preferential treatment for buses. The street classification policy defines a system of bus streets with the goal of improving bus level of service, travel times, and schedule adherence. But stops in the downtown are not well designed, signed, or located. The widening of the bus-passenger waiting islands along K Street from 6 to 13 ft and the installation of shelters is one step being taken to improve the situation. The city DOT will begin designing and installing attractive and functional bus shelters for the entire central business area in the fall of 1983.

The District of Columbia DOT intends to work closely with the private sector to develop transit incentive and transit promotion programs. A downtown transportation coordinator will be hired for this purpose. The coordinator will make available to employees WMATA's bus-rail combination flash pass and encourage employers to provide passes to employees at a discount, free, or in lieu of subsidized parking. The coordinator will have at his or her disposal a terminal so that transit information can be provided to employees by using WMATA's AIDS computerized schedule and routing information system. The coordinator will also provide printed transit information. The transit promotion program will work in concert with the parking management program to encourage a mode shift to transit.

The coordinator will also work with employees to develop flexitime programs to alleviate the peak load on the Metrorail and bus system, which will decrease operating costs. For example, for a 30 percent mode split, if 60 percent of travel occurs during the peak hour there will be 32 700 transit trips. However, if the peak hour generates only 50 percent of the transit trips, there will be 27 250 transit trips, or a reduction of 17 percent in required transit capacity.

Ridesharing

Policy actions to encourage ridesharing are recommended elements of the downtown plan. Office buildings, in particular, provide an excellent focus for ridesharing and other TSM programs. Developers, building owners, and employees will be asked to organize activities such as carpool matching, preferential parking for carpools and vanpools, distribution of transit passes, and staggered work hours. The proposed changes to the zoning regulations permit the amount of required parking to be reduced or eliminated if the building has a ridesharing program approved by the director of the city DOT.

The Washington Area Council of Governments (COG) is operating an areawide ridesharing program. Currently, COG has ridesharing coordinators representing the federal government, Virginia, and Maryland. However, no such person or activity exists for Washington (except the federal sector). The downtown transportation coordinator will work closely with COG, making use of their forms, data bases, and matching capabilities. The coordinator will work with employees to publicize the program, distribute ridesharing forms, obtain the matches on a terminal in his or her office, and, once a sufficient data base has been established, provide real-time matches at the employment site by using a portable terminal.

Parking Management

A balanced parking supply is necessary to support the objectives of the downtown plan. If an oversupply of inexpensive long-term parking is made available, there will be a strong incentive for the commuter to drive alone to work. A successful parking management program will reinforce transit, vanpool, and carpool travel and the walk- or bicycle-to-work trip and thus alleviate the problems associated with the enormous growth predicted for the downtown. The city DOT has been working closely with the Zoning Commission and the Board of Trade to develop new parking regulations for the downtown. The following are some of the modifications that have been proposed:

1. Reduction or elimination of parking requirements for buildings with a direct Metrorail connection or an approved ridesharing program or for buildings located in an area with a high level of public transit,
2. Reduction in the amount of required parking by up to 50 percent if it is located in a collective or shared parking facility,
3. Provision by hotels of off-street parking spaces for tour buses within a 4-mile radius of the hotel, and
4. Provision of bicycle parking spaces equal to or greater than 5 percent of the required number of automobile parking spaces.

The District of Columbia DOT has developed and is maintaining an up-to-date on- and off-street parking inventory within the downtown that shows the location, type, description, and characteristics of use. A microcomputer model has been developed for comparing the parking supply for each sector of the downtown with the demand for parking, given the mode split and automobile occupancy goals. The model can test the effect of various policy alternatives for five-year increments up to the year 2000. The city DOT is able to inform developers of the amount of parking to be provided consistent with its goals. Current trends indicate a parking supply that will be adequate for office-oriented needs and that will work toward lower automobile use. Relatively high prices and strong demand for spaces can be expected.

Complementary to these activities is the highly successful parking enforcement and adjudication program. Before the implementation of this program, a study found 4 illegally parked vehicles per block in close-in residential neighborhoods and 10 illegally parked vehicles per block in the downtown. The Bureau of Parking and Enforcement was established to perform parking studies, manage the parking meter operation, and enforce parking regulations. More than 50 civilian parking patrol aides issue tickets, and more than 450 illegally parked vehicles are towed each day. Cars belonging to scofflaws are immobilized by placing a Denver boot on the front tire. The owner must pay all outstanding fines plus a $25 booting fine before the vehicle will be released. The Bureau of Traffic Adjudication was established to process all parking offenses and remove this burden from the court system.

The residential parking permit program has also been very successful in helping the city achieve its transportation goals. Commuters had been parking in neighborhoods near the city center, major traffic generators, or major transit routes. Following a petition signed by a majority of the residents on a block, an investigation is conducted to determine whether at least 70 percent of the available spaces are occupied and at least 10 percent of the vehicles parked are from outside the District. If the street qualifies, signs are installed and permits are sold for $5/year.

Goods Movement

Although it is realized that goods movement activities are essential for the vitality of the city, unregulated truck access and loading will disrupt traffic operations and pedestrian activity. To minimize potential conflicts, an effective goods movement policy must deal with both the design of facilities (number, size, and location of curb cuts, alleys, and loading docks) and the time of day during which goods movement activities are permitted. Proposed amendments to the zoning regulations include the following topics related to goods movement:

1. Requirements on the size and number of loading berths have been modified to reflect better the actual need.
2. All loading berths are to be accessible directly from an improved alley or from private driveways that are 12-25 ft in width and lead to an improved alley. Access from a street is allowed only if approved by the director of the city DOT.

3. Curb cuts must be no closer than 40 ft to a street intersection for berths serving 30-ft vehicles and no closer than 55 ft for larger vehicles.
4. Joint loading berths serving two or more buildings are permitted.
5. The Board of Zoning Adjustment is authorized to reduce or eliminate the number of loading berths required and to approve the use of off-site loading facilities, including joint loading berths for buildings that front on a major pedestrian-emphasis street.

To ensure that goods delivery does not impede pedestrian and traffic movement within the downtown public right-of-way, the city DOT is considering putting time restrictions on certain activities and on certain streets where this is deemed appropriate. Goods movement and delivery criteria will be established for each street classification.

CONCLUSIONS AND SUMMARY

The District of Columbia DOT has developed a TSM program designed to maximize the use of public space in the downtown for the mutual benefit of all travel modes. This management plan is part of a new Master Plan for Downtown Washington, which includes a street classification system, a parking management program, public transit enhancements, carpool and vanpool incentives, improved pavement markings and signs, regulations governing the movement of goods, and improved safety and security for bicycle users.

This coordinated TSM planning effort is a result of the city DOT's analysis of the potential effects on the transportation system that could result from anticipated land development by the year 2000. Travel demand, mode choice, intersection and arterial capacity, transit needs, parking supply and demand, and goods movement were all examined. The findings of the analysis concluded that a balanced approach to transportation service delivery in the downtown was necessary if the livability and diversity goals set for the downtown were to be realized.

As the level of activity in the downtown increases, the TSM plan should provide for fewer conflicts among travel modes while affording a high level of service for all movements. A pedestrian network, for example, will be designed to provide safe and enjoyable pedestrian access to all portions of the downtown. Sidewalk clutter will be removed and vehicle intrusion minimized, which will result in improved pedestrian mobility. Streetscape guidelines will provide a high level of sidewalk treatment complemented by uniform signing and lighting. Automobile level of service will be maintained through the encouragement of the transit and ride-sharing modes, restrictions on goods delivery, and a limitation on curb cuts on major through-traffic routes. The existing downtown signal system is being replaced, which will greatly improve reliability. Metro buses will be given priority and will run more efficiently on bus-oriented streets.

The development community will be a major participant in the TSM program. Revised parking standards for new buildings will require carpool and vanpool spaces and encourage, through incentives, the establishment of transit incentive programs for tenants of new buildings. Thus, central-city employees will be encouraged, at the workplace, to rideshare or take transit.

These initiatives should improve the overall use of public space in the downtown and, over time, provide transportation services that will complement the objectives of the Master Plan for Downtown Washington.

REFERENCES

1. J. Fruin. Pedestrian Planning and Design. Maudep Press, New York, 1971.
2. Interim Materials on Highway Capacity. TRB, Transportation Research Circular 212, 1980.

Publication of this paper sponsored by Committee on Transportation System Management.

Making Progress with Traffic Restraint: The Role of Research

A.D. MAY

The range of measures proposed for restraining peak-period car traffic in urban areas is reviewed, and it is demonstrated that very few of them have been successfully implemented. Based on reported decisions and discussions with decisionmakers, the reasons for rejection of these proposals are identified and the strength of the criticisms made is assessed. Although the need for restraint is still not clearly demonstrated, it is concluded that traffic restraints can probably be justified as a means of improving efficiency and the environment and that fiscal measures are the most appropriate for further development. A number of issues are identified on which further research could usefully concentrate to ensure that future proposals can be more adequately formulated, and several new research developments in the United Kingdom that will contribute to this are mentioned.

The year 1983 marks the 20th anniversary of the publication in the United Kingdom of Traffic in Towns (1), a report whose influences are still felt in much of current policy on urban road provision, traffic control, and environmental management. Although many of its recommendations have found their way into practice, not just in the United Kingdom but around the world, one is particularly noticeable for its absence. Lord Crowther, in his preface to the report, said, "Distasteful though we find the whole idea, we think that some deliberate limitation of the volume of motor traffic in our cities in quite unavoidable." In practice, however, with one or two notable exceptions, politicians in the United Kingdom and elsewhere have avoided such limitations for the past two decades and show no signs of implementing a policy of traffic restraint in the near future. Why is this? Were Crowther and Buchanan and his team wrong in their analysis? Have the problems that necessitated restraint failed to materialize? Or are there adverse consequences of restraint that make otherwise worthwhile measures unacceptable? In the light of these answers, have traffic restraint a future role as an element of urban transportation policy? If so, what research is needed to promote that role?

This paper proposes to answer these questions by reviewing past attempts to implement traffic restraint, identifying where possible the reasons for their rejection, and assessing their importance. In particular, the need for restraint is reassessed and the limited evidence supporting restraints is demonstrated. Despite this, it is argued that restraint can still play an important role as part of a comprehensive urban transportation policy, and several avenues of research are suggested both to improve its technical feasibility and to understand its effects.

POSSIBLE METHODS OF TRAFFIC RESTRAINT

Traffic restraint measures can be defined as those that impose a restriction on vehicle use in order to achieve a significant modification in the mode, time, route, or destination of journeys. In the extreme case, this can result in a reduction in the total number of journeys made. Such a definition excludes most traffic management measures, such as junction controls, bus priority, and one-way streets, which at most impose a minor change in vehicle routing; it also excludes those measures that attempt to encourage a mode change by improving the alternative mode--e.g., fare subsidies, bus priority, and car-sharing schemes. It is less clear whether it should include measures such as traffic cell schemes, which impose significant changes in route without affecting mode or time of travel. Buchanan, however, considers these a separate set of measures, and they certainly have a more successful implementation history. They are therefore excluded from the following discussion.

Traffic restraint measures differ widely in the restrictions they impose. Physical restrictions are used, for instance, in street closures, barriers to through movement, and reductions in parking space. Delay-based restrictions arise when traffic signals are used to hold back traffic and occur naturally in the process of restraint by congestion. Regulatory restrictions limit the use of transportation facilities to certain vehicles--for instance, by imposing weight or length limits, permitting only short-duration parking, or requiring a permit to use a particular road. Fiscal restrictions impose a charge for the use of facilities, whether they be to park, to enter a particular area, or to use the road system generally, as in the concept of road pricing. It is important throughout to differentiate between those measures that impose restrictions on the parked vehicle and those that control the moving one.

The following discussion outlines briefly a number of proposed and implemented schemes, which are described in more detail elsewhere (2). They do not attempt to be comprehensive, particularly because many proposed but abandoned schemes are never publicized. For simplicity, they concentrate on restrictions on peak-period car movements, which were the main focus of Buchanan's recommendations and of later studies.

Parking Controls

Most studies in the United Kingdom in the 1960s proposed parking controls as the most readily available method of traffic restraint. Both motorists and transportation planners had already experienced the use of on-street parking controls to reduce the congestion and hazard caused by the parked vehicle and, since such controls frequently reduced on-street parking accumulation by two-thirds, it seemed reasonable to assume that the extension of such controls would be an effective means of traffic restraint. However, as a means of imposing restraint, on-street parking controls alone are clearly inadequate. Typically, they only involve between a tenth and a third of all city-center parking stock (3), and other types of parking also require control if trip ends are to be reduced rather than simply transferred to off-street parking spaces.

A range of measures has been proposed for controlling off-street parking space. Physical controls involving restrictions on provision of new space are now a common element of planning control but have no effect on existing space. Several proposals have been made for extending these measures to the closure of existing spaces. London had a program of closing temporary public car parks in the late 1970s, and Santiago has done so more recently. More wide-ranging plans for reduction of private off-street parking have, however, not been implemented. The U.S. Environmental Protection Agency plan for reducing off-street parking in Boston was abandoned, and suggestions in the United Kingdom in 1976 for using standard reduction orders or taxation to do so (4) never became law although they still have their advocates (5).

Regulatory controls have been less frequently advocated. Apart from some attempts to close car parks until after the peak period, most restrictions on the type or manner of parking have been introduced for reasons other than restraining traffic.

Pricing is the most commonly proposed control, but it is inevitably limited to public car parks, and it is difficult to find examples where it has been imposed comprehensively enough to do more than divert users to different facilities. San Francisco introduced a tax surcharge of 25 percent in 1970, but this was primarily for fiscal reasons (6). Singapore increased charges at all central-area car parks by between 30 and 50 percent in conjunction with its 1975 area licensing scheme (7). The Greater London Council has had powers since 1969 to control the way in which privately operated public car parks operate, and it proposed in 1976 to specify minimum charges throughout central London that involved increases for all-day parking of up to 200 percent (8). However, the proposal was abandoned, and the powers are still unused. In 1981, the U.S. Urban Mass Transportation Administration (UMTA) introduced an experiment with increased parking charges in Madison, Wisconsin. Originally planned to involve five car parks, the experiment was later limited to four, which represented 30 percent of public off-street spaces and 6 percent of all spaces; charges for long-term parking were increased by 55 percent.

Even where comprehensive on- and off-street pricing policies can be introduced, they have no influence on private parking spaces, which typically represent between one- and two-thirds of the parking stock (3). It appears from proposals to date that only reductions in supply have been considered for these spaces, and there is no sign of these being implemented. Even were they to be imposed, parking restrictions would have no effect on through traffic, which frequently represents as much as a third of the traffic entering central areas.

Controls on Moving Vehicles

Faced with these two major shortcomings of parking controls, more interest has been expressed in the

Table 1. Public objections to U.S. and London area licensing plans.

Objection	United States	London
Interferes with right to travel	Major objection	Royal Automobile Club campaign issue
Harms business	Major objection	
Discriminates against those with special needs		56 objections
Discriminates against poor	Major objection	30 objections
Hard to enforce	Minor objection	38 objections
Hard to administer		26 objections
Overloads transit	Minor objection	88 objections
Relocates traffic problems	Minor objection	22 objections
Requires legislative clearance	Minor objection	

possibility of restricting the moving vehicle. Physical restrictions have typically been applied only to reroute traffic away from environmentally sensitive areas, and most of these, including the U.S. experiments with automobile-restricted zones (9), cover such restricted areas that the measures do not have much restraining effect. The largest schemes are in the centers of European cities such as Gothenburg (10) and Groningen (11), where the whole center is divided into four or five cells, each accessible only from a ring road. Even these schemes primarily reroute through traffic, although there is some evidence from Groningen that there has been a reduction in the amount of traffic that terminates in the city center (11).

Delay-based restraint has been proposed on several occasions, including in studies for London (12) and Sheffield (13), but has been attempted only once, in the short-lived zones-and-collar experiment in Nottingham in 1975 (14), which involved the use of bus lanes and traffic signals to increase travel time for city-center-bound traffic.

Proposals for regulations to restrict certain types of vehicle are not uncommon but are frequently limited to the larger commercial vehicles. Among the schemes proposed for restricting car use are a 1976 proposal for allocating permits for entry to central London only to those who could demonstrate a special need (15), simple permit-based restrictions in one or two smaller Italian cities, a scheme introduced in Lagos, Nigeria, in 1977 in which odd- and even-numbered vehicles are only permitted entry to Lagos Island between 5:00 a.m. and 6:00 p.m. on alternate days, and regulations introduced in May 1982 that ban cars from central Athens for 8 h/day.

However, fiscal restrictions have been the measure most commonly discussed. The idea of road pricing, in which an in-vehicle meter records the amount of use of congested roads and the vehicle owner is charged the cost of the congestion that he or she imposes on others, was recommended in the United Kingdom in 1964 (16) and in the United States as early as 1956 (17). No one has yet implemented such a scheme or even publicly tested the necessary equipment, although much developmental work took place in the United Kingdom in the late 1960s (18). Few now advocate such complex pricing systems, but there have been many proposals for simpler charging methods.

In 1974 and again in 1979, the Greater London Council brought forward proposals for supplementary licensing, a concept in which cars entering central London would have to purchase special licenses (19, 20). Both proposals were rejected, although the latter has since been reintroduced for discussion (21). Similar suggestions have been made and rejected in Bristol, Stockholm, Kuala Lumpur, and Bangkok. In the United States, UMTA spent some time trying unsuccessfully to find a U.S. city willing to experiment with such a measure. Only one city, Singapore, has successfully implemented such controls: In 1975, cars entering the Singapore city center with fewer than four occupants between 7:30 and 9:30 a.m. were required to buy a license costing $1.25/day. Both the period of control and the charge have since been increased (7).

Finally, the use of existing taxes either on car ownership or on fuel has occasionally been advocated as a restraint mechanism. In practice, these are usually too blunt as instruments designed to achieve specific restraint needs, but they may be appropriate in a few predominantly urban states. Hong Kong has recently demonstrated this by doubling the car purchase tax and trebling the car ownership tax while rejecting other methods of reducing traffic (22).

REASONS FOR REJECTION OF PROPOSALS

As the brief review above has indicated, the failure rate in the development of traffic restraint proposals has been very high, and it would clearly be informative, in assessing the future role of restraint, to study the reasons for the rejection or abandonment of so many of these proposals. In practice, such information is hard to come by; few politicians have made public their reasons for rejection, and even where they have the relative importance of the reasons given is rarely stated. Only two published records of reasons for rejection are available: One relates to the first proposal for supplementary licensing in London (23) and the other to attempts by UMTA to find the U.S. city willing to experiment with similar controls (24). What follows is based on these and informal discussions with those involved in decisions elsewhere; it clearly is less than comprehensive. Table 1 summarizes the public's objections to the London scheme and cities' objections to the U.S. proposals.

Issues similar to those in Table 1 have arisen elsewhere. Car park licensing proposals in London encountered objections that it was unnecessary, would be ineffective, would hasten the decline of central London, would overload public transportation, and would be inequitable and unduly expensive. Proposals for reducing or taxing private parking spaces were abandoned on the grounds that they would be difficult to enforce, would encourage fringe parking, and would be inequitable; in particular, they were considered an unfair imposition on businesses, which had been required to provide the spaces in earlier planning legislation. The zones-and-collar experiment in Nottingham was abandoned as ineffective (14), and similar proposals for London were dismissed because they would have been ineffective, inefficient, and unduly disruptive to essential users.

Various reasons have been given for abandonment of the several supplementary licensing proposals, including doubts as to the need for them and their effects and the public acceptability of such an obvious restriction on freedom of vehicle use. It is possible to categorize these reasons under the following broad headings:

1. The restraint would be unworkable (administratively or from the standpoint of enforcement).
2. The restraint would be ineffective (in that the net response to the penalty imposed would be insignificant).
3. The restraint would have adverse effects on transportation (by diverting traffic or overloading public transportation).
4. The restraint would cause economic activity to relocate.

5. The restraint would be unfair to certain groups in society (the poor, essential users, and others).
6. The restraint would involve an unacceptable restriction on freedom of movement.
7. The restraint would be unnecessary.

It is useful to consider each of these reasons in turn to identify the strength of the arguments and the further research that is necessary if the issues involved are to be further clarified.

Restraint Would Be Unworkable

The practicability of individual measures should be relatively easy to demonstrate. Regulation, administration, and enforcement procedures can all be developed and pilot tested before implementation and their costs set against the anticipated benefits of the scheme. Even so, this is a surprisingly frequent objection. In some cases, the objection seems valid: The Nottingham experiment demonstrated the impossibility of imposing more than 2 or 3 min of delay for lack of queue storage space (14), and proposals in London for permits based on need foundered on the problems of defining need and checking the validity of applications (20).

However, doubts about enforcement, particularly, often result in potentially workable schemes being rejected. For example, the 1974 proposal for supplementary licensing in London involved using 400 wardens to carry out random roadside checks and stop apparently violating drivers. Even this relatively labor-intensive method would, with about 90 percent compliance, have consumed only 6 percent of the license revenue (25); yet the proposal was considered unworkable by politicians and public. However, Singapore demonstrated that by checking all vehicles entering, without stopping offenders, 98 percent compliance could be achieved at a cost equivalent to 5 percent of revenue (7).

Such suspicions concerning the feasibility of enforcement are perhaps not surprising, given the poor record of enforcement of existing on-street controls; it is estimated, for example, in central London that there are between 0.25 and 0.5 m offenses/day, only 2 percent of which are detected and only 1 percent of which result in fines (26). However, there has also been a marked reluctance politically to take any of the steps that could improve compliance: increased manpower, less labor-intensive methods, higher penalties, or reductions in the checks necessary to protect the innocent motorist (26). There has also been a failure technically to understand the nature of the relation between chance of detection, level of penalty, and compliance, although some work is now being done on this (27).

Restraint Would Be Ineffective

The second criticism is harder to refute, since it requires a demonstration that a penalty can be imposed on a large enough proportion of journeys and that those affected will respond to a significant extent. The types of penalties outlined above are removal of parking or road space for all or selected users, additional time through delay or longer routing, and price. Removal of supply will have the most direct effect: Provided that supply is reduced to below demand or some users are specifically denied access, there will be an inevitable reduction in use. However, such restrictions are notoriously difficult to make effective.

Parking supply is sufficiently flexible for existing sites to absorb more cars if others are closed; street closures with access exemptions attract violations. Experience has shown that sizable delays are difficult to impose; Nottingham could only impose 2-3 min of delay because of lack of queue storage space and signal violations (14), studies in London produced similar findings (12), and even diversion around a city-center traffic cell scheme to reach a cell on the far side would only add at most 5 min to journey times. Given the total cost of journeys to work, such small penalties are unlikely to have a significant effect.

There are no such limits, however, on the extra price that can be imposed on a journey; the uncertainty here concerns the ability of motorists to pass on the costs to others and the size of response of those who cannot. In countries such as Sweden, where commuting costs are tax-deductible, price is clearly less effective; so it may be in countries such as the United Kingdom, where the costs of a large proportion of car users are met by their employers. There are some hypothetical indications that employers who subsidize their employees' journey to work would refuse to pay large increases in the costs of car use (28), but the extent to which such costs can be passed on is generally little understood.

So, too, is the overall scale of response to price. Studies of response to petrol price increases suggest short-run arc elasticities of -0.1 to -0.3 (29); for all-day parking charges, values range from -0.3 to -1.2 (30), but these are increased by the availability of alternative facilities. A study of responsiveness to peak-period tolls on an isolated bridge crossing found values of between -0.2 and -0.5 (31). None of these ranges of values can reliably be used to estimate the effects of supplementary licensing, which would involve a much higher cost increase and a different form of charge. However, experience in Singapore, where a charge of \$1.25 produced a 44 percent reduction in traffic entering the city center, indicates that the response to such penalties can be considerable (7).

The proportion of users not subject to control is clearly also a crucial determinant of effectiveness. Experience in London has demonstrated this weakness with parking controls: While on-street and public off-street parking fell by a third over a 12-year period, private parking and through traffic both doubled, which resulted in a one-third increase in traffic entering the city center (32). In a similar case, experience in Lagos suggests that exempting half the vehicles on any day enables them to increase their use of the road to the detriment of the control's effectiveness. Clearly, if exemptions are to be provided, a very careful balance is required between fairness and effectiveness.

Restraint Would Have Adverse Transportation Effects

Those restrained from traveling will almost always make alternative journeys by different routes or modes, at different times, or to different destinations. Restraint may provide the spare capacity for some of these new demands; for example, reduction in radial traffic may permit more orbital traffic, or faster buses may provide more capacity. However, most new demands will impose some new costs. In the case of parking controls, traffic that parks on the fringes of the control area may well impose substantial environmental or traffic disruption; with moving-vehicle controls, diverted through traffic may cause an increase in congestion on the orbital route around the control area. Both types of measures may well encourage new peaks immediately before and after the control period, stimulate growth in car sharing, and require additional capacity on public transportation that, if used only in the peak period, will worsen the economics of public transportation operations. Some of these effects--particularly the changes in parking location, time of travel, and car occupancy--will be difficult to predict, and it may be difficult for politicians to conceive of already overburdened ring roads or bus services accommodating more traffic.

The true size of these effects is probably only adequately determined by experiment, but the question will still arise as to whether the resulting costs outweigh the benefits of restraint. In the one adequately documented experiment, in Singapore, the area license scheme resulted, after some adjustments, in a 20 percent reduction in ring road speeds and a 10 percent increase in flow after the control period (7). Singapore's politicians considered both of these acceptable in view of the direct benefits resulting from the 44 percent reduction in central-area traffic.

Restraint Would Cause Economic Activity to Relocate

The short-term effects on travel considered above can to some extent be predicted and can be relatively easily measured by experiment. The longer-term effects on economic activity are much more difficult to predict and, because they are less reversible, are more serious causes of concern. The suggestion is made that increased travel costs will encourage employees and customers to take their labor and business elsewhere and that firms will necessarily leave the control area as a result, thus exacerbating trends that are already apparent, and relocating activities in areas where control of travel demand is far more difficult. Conversely, it can be argued that reduced congestion and an improved environment would make the area a more attractive one in which to work or shop and reduce the costs of doing business, thus strengthening the area's economic base. It is notoriously difficult to isolate such processes (11) and, although studies have demonstrated that firms may exaggerate such effects in the short term (33), few models have attempted to predict the longer-term responses of employees and firms to transportation changes. One prediction for Leeds suggests that a high city-center parking charge would cause 20 percent of city-center jobs to relocate to the suburbs, where, of course, traffic restraint would be more difficult to impose (34). However, even this model excludes many of the benefits of restraint to employers and employees.

Restraint Would Be Unfair to Certain Groups in Society

Perhaps the most fully analyzed criticism of restraint policies is that restraint would be unfair to certain segments of society, although much of the debate centers on the nature of fiscal controls (i.e., their regressiveness, etc.) (35). In practice, much depends on the relative numbers of the wealthy and poor who currently use cars in the area to be controlled, their relative sensitivity to charges, and the extent to which improved conditions for poorer bus users can be considered to outweigh the adverse effects on poorer car users. One analysis suggested that the poorest third of London residents made only 12 percent of the car journeys to central London, which represents only 2 percent of all journeys there, but they were three times more likely to use a bus and hence to benefit from traffic restraints (36). It is interesting that the study in Singapore found no difference between wealthy and poor car drivers in responsiveness to price (7). It is also interesting to note that such equity issues are frequently raised with charges of car use but seldom with charges for parking.

Contrasts between rich and poor are not the only distributional implications of restraint that are of interest. One criticism of supplementary licensing in London was that it would impose undue hardship on those who had no choice but to use cars. In practice, analysis suggested that those who made frequent use of their vehicles would more than recoup the license fee in journey time saved (25). This clearly was not the case with the Nottingham zones-and-collar experiment, in which all drivers incurred penalties that could not be outweighed by savings elsewhere if the principle of restraint by delay was to be successful. Similarly, bans on parking at certain times or for certain durations and restrictions on certain vehicles on certain days have a considerable element of rough justice that will adversely affect essential users. Generally, the analysis of such distributional effects is difficult because it requires the individual groups of concern to be separately identified and the implications of penalties and exemptions on each group to be separately estimated.

Restraint Would Involve Unacceptable Restriction of Freedom of Movement

No analysis can refute the argument that traffic restraints would restrict the freedom of movement of car drivers. The issue is clearly a matter for political debate. However, unless such freedom is considered sacrosanct, restraint measures that in other terms produce net benefits will presumably justify some infringement of drivers' freedom. The strength of this argument, therefore, needs to be judged in the context of the arguments above about the adverse effects of restraint and those below about the need for restraint.

Restraint Would Be Unnecessary

Clearly, if the argument that restraints are unnecessary is upheld, the issues raised above under the other arguments are irrelevant. Particularly because traffic restraint imposes restrictions on some members of the community, it is essential that it be presented as a means to clearly defined ends and that it can be demonstrated that other, more acceptable measures are not available. The evidence on these issues has been reviewed elsewhere (3) for the United Kingdom, and it is clear that little information is available on the scale of the problems to be overcome (37). The lack of references in the international literature suggests that such information may also be lacking elsewhere.

The arguments presented against each of the potential objectives of restraint can be briefly summarized as follows.

Efficiency

Reducing the congestion costs imposed by each vehicle on others has always been one of the objectives of restraint (38), and various attempts to cost such congestion have produced estimates in the range of $1 billion to $2 billion/year for the United Kingdom. However, there are few data on trends in congestion, particularly urban-area speeds, and what there is suggests that conditions are, if anything, improving (39). This information for provincial U.K. cities has been used to argue that the true costs and achievable improvements in congestion have been grossly exaggerated (40). Somewhat against the trend, however, recent central Longon figures suggest a 15 percent reduction in peak-period speeds and a 10 percent reduction in the off-peak between 1974 and 1980 (41). In developed cities, trends in congestion may worsen or improve depending on the ability to manage transportation systems better and on rates of growth or decline in city-center activities. However, in the developing world it is clear that congestion is not only already more severe but is rapidly getting worse (42). Generally, it appears that the ability to reduce congestion significantly in the short term by means other than restraints is severely limited (43).

Resource Conservation

Traffic restraint has been proposed as a means of saving not only the resources required in road construction but also the fuel consumed in private vehicle use. However, the contribution to national energy saving of city-center traffic restraint is so small that local authorities seem unlikely to accept such restrictions in the interests of fuel economy. For example, one U.K. study estimated that a 50 percent reduction in car use for all urban journeys to work would only reduce national energy consumption by 2 percent (44).

Environmental Improvement

Many traffic restraint measures have been proposed on environmental grounds, and there are clear indications that many environmental improvements can only be achieved in the short term by restraint. However, the seriousness of environmental problems is less clear. There has been only one national survey of attitudes to the environment in the United Kingdom, in 1972 (45) and, although that showed that two-thirds of the population were concerned about danger as pedestrians and half about noise and fumes in the street and noise at home, it says nothing about trends in attitudes since then or the extent to which such concern justifies restrictions on car use. Indeed, some measures that have both restricted accessibility and improved the environment in residential areas have been rejected by residents who considered the environmental improvements not worth the resulting loss in accessibility (46).

Land Use Planning Goals

It has often been argued that congestion is encouraging firms to decentralize, that the adverse environment is encouraging residents, shoppers, and employees to leave city centers, and that by tackling these problems traffic restraint can help revitalize the center (9,10). There is some evidence that pedestrian streets, at least, have this effect (47). However, not only is restraint only one means of achieving these ends, but, as noted above, it may well have the reverse effect.

FUTURE ROLE OF RESTRAINT

Many of the arguments in favor of traffic restraint have in the past rested on largely unsubstantiated claims of severe transportation problems to be overcome or appeals to the apparent logic of restricting private users in favor of public transportation and the pedestrian. Given the distributional effects of restraint and its possible adverse consequences, such arguments are hardly acceptable. As the above analysis has shown (3), there does not appear to be a defensible case for traffic restraint as a necessary means of achieving energy conservation, financial, land use planning, or equity objectives. However, analysis of both the efficiency and environmental objectives suggests that, if there is a clearly demonstrated need for significant improvements, restraint is the only method available in the short term to achieve them. There is little evidence available to confirm that significant improvements are required, but it seems likely that there will at least be some cities where they are. In such situations, the implementation of traffic restraint measures as part of a comprehensive policy of public transportation improvement, limited upgrading of bypass routes, and environmental treatment seems most likely to be able to achieve the desired results with the minimum adverse side effects.

As to the types of measures that are most appropriate, evidence to date indicates clearly that delay-based measures are likely to be counterproductive, physical or regulatory bans unduly harsh on essential users, and parking controls on their own insufficiently comprehensive. On the other hand, simple fiscal controls such as supplementary licensing have been shown to be effective and sufficiently flexible (particularly if combined with a system of exemptions) that most of their disadvantages can be overcome. It seems sensible to concentrate further work on such measures, although there may also be a role for comprehensive parking controls if they can be combined with effective restrictions on through traffic.

FURTHER RESEARCH NEEDS

However, it is clear that more work will be required before policymakers are prepared to adopt such measures. The above analysis suggests that this research should fall into three areas: (a) the need for restraint, (b) the effects of restraint, and (c) the practical requirements of restraint. Some suggestions under each of these headings are made below.

Restraint Needs

If traffic restraint is to be justified solely on efficiency and environmental grounds, then the severity of these problems needs to be demonstrated. There is currently little evidence on trends in travel time in urban areas and even less on travel time variability. This appears to be largely because sufficiently low cost and statistically reliable survey methods have yet to be provided. Work on the development of such techniques and the understanding of patterns of travel time variability has recently started (48), but more work is needed, particularly for public transportation users.

More information is also required on the extent of environmental problems. Here the difficulty is not one of measuring levels of noise pollution or visual intrusion but of understanding their implications and particularly the extent to which increased costs to travelers can be justified to achieve given levels of environmental improvement. This is a particularly difficult area, as attempts to cost the effects of traffic noise have shown, but it clearly merits further work.

Restraint Effects

Several issues arise concerning the effects of traffic restraints. First is the question of response to controls. As others have noted (49), there is a need to develop greater understanding of elasticity with respect to car use charges, perhaps by analyzing parking charges, tolls, and fuel prices as elements of generalized cost and calculating elasticities in these terms. Motorists' ability to pass on the costs of car use and the implications of this for such elasticities also require further study, although some preliminary work has already been done

(50). As a separate issue, response to supply constraints and costs paid by those who do not respond need to be more fully understood if they are to be used as a restraint mechanism. Some work has been done in studying response to bridge closures (51-53), but this may not adequately represent reaction to permanent, as opposed to emergency, closures. Finally, in this group of issues is the question of response by those on whom penalties are not imposed. The response of through traffic is of particular concern, since growth in through traffic and excessive diversion can both seriously undermine the benefits of restraint (54).

The second issue is that of the resulting transportation effects. In addition to the rerouting effects mentioned above, for which more detailed assignment-simulation models are now available (55, 56), there is a need to be able to predict response by peak spreading and car sharing, both of which Singapore showed to be attractive alternatives to solo car use (7). Behavioral car-sharing models now exist (57) but have yet to be integrated into analytic packages; such models have yet to be developed for peak spreading. Similarly, locational response to parking controls requires further study, and some work has recently started on this (58).

The third issue is the longer-term relocational response of economic activity. As indicated above, there have been recent developments in models that incorporate longer-term movements of households and jobs (34). However, they do not as yet include responses of firms themselves, particularly to issues such as environmental improvements and operating cost reductions, which may be important benefits of traffic restraint.

The final issue is the distributional effects of restraint, which, as noted earlier, require predictions of response of and impact of exemptions on different groups of users. Some of these, such as residents and business travelers, can be readily identified from existing models, but others will require more detailed analytic tools.

These research issues are not necessarily best answered by the development of further predictive models; in many cases, more faith can be placed in studies of people's reactions to actual changes. In some cases, opportunities arise to measure reactions to the changes introduced by specific restraint measures; the studies in Nottingham and Singapore are good examples. However, it is one of the basic dilemmas of research on traffic restraint that, although some experience of such measures is needed in order to understand and predict their effects, one is unlikely to find many authorities willing to experiment with restraint measures and hence provide the necessary experience, in the absence of adequate predictions.

One partial solution to this problem is to take more advantage of unplanned increases in the cost of using the transportation system as was the case with the bridge closure studies mentioned above (51-53). Such opportunities are themselves (fortunately) rare, and careful planning is required if advantage is to be taken of them.

Practical Requirements

It appears that the main need here is to develop improved enforcement methodologies and equipment. Indeed, there is a general need in the field of traffic management for a better understanding of the effects of different levels of compliance on effectiveness (59) and of the relation between compliance, chance of detection, and level of penalty (27). Separately, concern over the manpower implications of enforcement suggests the need for further study of more automated detection techniques, such as automatic vehicle identification (60).

Such a long list of research requirements seems rather daunting and may only be justifiable if the political will is there at least to consider restraint further. However, many of the research needs identified will have wider benefits in the field of transportation policy assessment. It is to be hoped that some at least will be pursued and will enable future restraint proposals to be considered with less scepticism and greater understanding.

REFERENCES

1. C. Buchanan and others. Traffic in Towns. Her Majesty's Stationery Office, London, 1963.
2. A.D. May. Traffic Restraint: Proposals and Practice. Transport Reviews (in preparation).
3. A.D. May. How Far Can We Go with Traffic Restraint? Public Works Congress Papers, Birmingham, England, 1981.
4. The Control of Private Nonresidential Parking: A Consultation Paper. U.K. Department of the Environment, London, 1976.
5. House of Commons Transport Committee. Transportation in London. Her Majesty's Stationery Office, London, 1982.
6. D.J. Kulash. Parking Taxes as Roadway Prices: A Case Study of the San Francisco Experience. Urban Institute, Washington, DC, WP 1212-9, 1973.
7. P.L. Watson and E.P. Holland. Relieving Traffic Congestion: The Singapore Area License Scheme. World Bank, Washington, DC, SWP 281, 1978.
8. Draft Regulations for the Control of Off-Street Parking. Greater London Council, London, 1976.
9. W.S. Herald. Auto Restricted Zones: Plans for Five Cities. UMTA, Rept. UMTA-VA-06-0042-78-32, 1977.
10. C.M. Elmberg. The Gothenburg Traffic Restraint Scheme. Transportation, Vol. 1, No. 1, Amsterdam, 1972.
11. A.D. May and P.M. Weaver. Monitoring the Impact of Traffic Management on Retailing Activities: Problems and Possible Solutions. TRB, Transportation Research Record 812, 1981, pp. 33-39.
12. J.A. Cracknell and others. Physical Restraint: Greater London's Cordon Restraint Study. Traffic Engineering and Control, Vol. 16, No. 9, London, 1975.
13. P.S. Coventry and K. Dickinson. Sheffield and Rotherham L.U.T.S.: Urban Traffic Control for Sheffield. Traffic Engineering and Control, Vol. 18, No. 7, London, 1977.
14. R.A. Vincent and R.E. Layfield. Nottingham Zones and Collar Study: Overall Assessment. Transport and Road Research Laboratory, Crowthrone, Berkshire, England, LR 805, 1977.
15. R. Lane and D.M. Hodgkinson. A Permit System for Traffic Restraint. Traffic Engineering and Control, Vol. 17, No. 3, London, 1976.
16. U.K. Ministry of Transport. Road Pricing: The Economic and Technical Possibilities. Her Majesty's Stationery Office, London, 1964.
17. M. Beckmann, C.B. McGuire, and C.B. Winsten. Studies in the Economics of Transportation. Yale Univ. Press, New Haven, 1956, Chapter 4.
18. G. Maycock. Implementation of Traffic Restraint. Transportation and Road Research Laboratory, Crowthorne, Berkshire, England, LR 422, 1972.
19. Supplementary Licensing. Greater London Council, London, 1974.
20. Area Control. Greater London Council, London, 1979.
21. Area Control: A Summary of the Problems and Issues. Greater London Council, London, 1982.

22. Crackdown on Motorists. South China Morning Post, Hong Kong, May 6, 1982.
23. A.D. May. Road Pricing: Should and Might It Happen? A Comment. Transportation, Vol. 8, No. 2, Amsterdam, 1979.
24. T. Higgins. Road Pricing: Should and Might It Happen? Transportation, Vol. 8, No. 2, Amsterdam, 1979.
25. A Study of Supplementary Licensing. Greater London Council, London, 1974.
26. A.D. May. Parking Enforcement. Traffic Engineering and Control, Vol. 23, No. 6, 1982.
27. J.R. Elliott and C.C. Wright. The Collapse of Parking Enforcement in Large Towns: Some Causes and Solutions. Traffic Engineering and Control, Vol. 23, No. 6, 1982.
28. S. Zuckerman. Business Assisted Motoring: A Pilot Study of Employers' Attitudes. Greater London Council, London, RM 515, 1977.
29. D. Banister. Transport Policy and Energy. Univ. College, London, Discussion Paper 36, 1981.
30. R. Tong. Parking Price Elasticities: A Review. Leeds Institute for Transport Studies, Univ. of Leeds, Leeds, England, 1982.
31. S. Atkins. The Price of a Toll. Surveyor, April 1981.
32. A.D. May. Parking Control: Experience and Problems in London, Traffic Engineering and Control, Vol. 16, No. 5, 1975.
33. A.D. May and P.M. Weaver. Comprehensive Traffic Management in York: The Effects on Trade. Traffic Engineering and Control, Vol. 22, No. 4, 1981.
34. R.L. Mackett. The Impact of Transport Planning Policy on the City. Univ. of Leeds, Leeds England, Ph.D thesis, 1982.
35. C.D. Foster. Evidence to the Greater London Development Plan Inquiry on the Regressiveness of Road Pricing. Inquiry Background Paper 654, London, 1971.
36. A.D. May. Supplementary Licensing: An Evaluation. In Urban Transportation Economics, TRB, Special Rept. 181, 1978, pp. 30-38.
37. A.D. May. Can Traffic Control Strategies Satisfy Current Objectives? Proc., ATEC Conference, Paris, France, 1980.
38. R.J. Smeed. Traffic Studies and Congestion. Journal of Transport Economics and Policy, Vol. 2, No. 1, 1968.
39. Urban Congestion Study 1976. U.K. Department of Transport, London, Interim rept., 1978.
40. U.K. Department of the Environment. Transport Policy: Consultation Document. Her Majesty's Stationery Office, London, Vol. 2, Paper 3, 1976.
41. Traffic Monitoring Review (1981). Greater London Council, London, 1981.
42. Urban Transport Sector Policy Paper. World Bank, Washington, DC, 1975.
43. A.D. May. Breaking the Habit: The Challenge of Transport Management. Leeds Univ. Review, Leeds, England, 1980.
44. D. Maltby and others. An Analysis of Energy Use by Passenger Transport in the UK. Traffic Engineering and Control, Vol. 18, No. 12, 1977.
45. J. Morton-Williams and others. Road Traffic and the Environment. Social and Community Planning and Research, London, 1978.
46. W.A. McKee and M.J. Mattingly. Environmental Traffic Management: The End of the Road. Transportation, Vol. 6, No. 4, 1976.
47. H. Simkowitz, C. Kissling, and A.D. May. Land Use. In Background Papers on Urban Transport and the Environment. Organization for Economic Cooperation and Development, Paris, 1979.
48. A.D. May and others. Monitoring Urban Congestion: Current Practice and Research Needs. Institute for Transport Studies, Univ. of Leeds, England, 1982.
49. Evaluation of Urban Parking Systems. Organization for Economic Cooperation and Development, Road Research Rept., Paris, 1980.
50. M.C. Dix and H.R.T. Pollard. Company Car Financing Practices and Impacts on Travel Patterns. Proc., PTRC Summer Annual Meeting, London, 1981.
51. Charles River Associates. Surveying Traveller Behaviour Following the Collapse of the Tobin Bridge. Transportation Systems Center, U.S. Department of Transportation, Cambridge, MA, Rept. DOT-TSC-722, 1972.
52. J.A.L. Dawson. Comprehensive Traffic Management in York: the Monitoring and Modelling. Traffic Engineering and Control, Vol. 20, No. 11, 1979.
53. T.R. Lee and L.J. Wood. Adjustments in the Urban System: The Tasman Bridge Collapse and Its Effects on Metropolitan Hobart. Pergamon Press, Oxford, England, 1981.
54. A.D. May. Traffic Restraint: Can Further Research Aid Its Development? Proc., World Conference on Transport Research, Crowthrone, TRRL, 1980.
55. M.D. Hall and others. SATURN: A Simulation/Assignment Model for the Evaluation of Traffic Management Schemes. Traffic Engineering and Control, Vol. 21, No. 4, 1980.
56. D.R. Leonard and others. CONTRAM: A Traffic Assignment Model for Predicting Traffic Flows and Queues During Peak Periods. Transport and Road Research Laboratory, Crowthorne, Berkshire, England, LR 841, 1978.
57. P.W. Bonsall. Microsimulation of Car Sharing: A Description of the Models and Their Calibration. Transport and Road Research Laboratory, Crowthorne, Berkshire, England, SR 564, 1980.
58. P.W. Bonsall and H.C.W.L. Williams. Development of a Policy Responsive Parking Model for the Peak Period. Institute for Transport Studies, Univ. of Leeds, Leeds, England, research proposal, 1981.
59. M.R. Wigan and T.J. Bamford. Parking Policy When Enforcement is Limited. Transport and Road Research Laboratory, Crowthorne, Berkshire, England, SR 75, 1974.
60. R.S. Foote. Collection Problems and the Promise of Automatic Vehicle Identification. TRB, Transportation Research Record 494, 1974, pp. 15-20.

Publication of this paper sponsored by Committee on Transportation System Management.

Getting Results from TSM Planning: Baltimore's Corridor Study Approach

DONALD R. SAMDAHL, JOEL REIGHTLER, AND SANDRA S. LIPPMAN

A series of transportation system management (TSM) corridor studies was performed in the Baltimore region in conjunction with 1982 transportation control plan (TCP) activities. The primary objective of the studies was to identify specific implementable TSM actions that could improve the performance of the transportation system and reduce automobile emissions and energy consumption. A total of 27 corridors were initially selected for study, of which 7 were completed in preparation of the TCP. A detailed analytic and management approach was developed in order to conduct each corridor study efficiently. Continuing technical and policy guidance was provided by a project management committee consisting of federal, state, and local agency personnel. Public participation was also a major element of the process and provided valuable insight into local transportation concerns. A wide variety of TSM actions was considered, including traffic operations, transit programs, ridesharing, parking management, commercial vehicle programs, and bicycle and pedestrian programs. Each alternative action was evaluated by using several measures of effectiveness. The recommended TSM actions, with responsibilities specified, were grouped into packages as part of the implementation plan. The recommended TSM actions were found to be effective in meeting the project objectives, contributing significantly to the improvement of transportation services and the environment. Finally, the study process was determined to be transferable to other corridors in the region and has since been used for additional TSM studies.

In preparation for the 1982 transportation control plan (TCP), the Baltimore Regional Planning Council (RPC) initiated a major planning effort in 1979 to pursue intensive examination of the measures that had been identified in the 1979 TCP for further study or implementation. The transportation system management (TSM) and TCP activities were combined into a single TSM-TCP program to avoid duplication of effort.

The major emphasis was placed on implementation. The primary objective of the TSM-TCP planning was to identify specific TSM measures that could be implemented to improve the performance of the transportation system and reduce automobile emissions and energy consumption. A serious shortcoming of TSM planning to date had been its inability to stimulate implementation of significant TSM improvements.

Up to that time, the main approach to TSM planning was to study individual measures on a regional scale, mostly to investigate overall feasibility and impact, and to resolve major institutional constraints. However, this approach often failed to reach the level of detail needed to identify specific applications. Although this type of regional study was still needed, particularly for previously unstudied measures, a more detailed level of study was necessary to identify specific TSM projects.

To expedite the selection of implementable TSM projects, a series of corridor-subarea studies was initiated to allow site-specific analysis of problems and opportunities amenable to the application of TSM strategies. These were intended to be reasonably low in cost and fast-paced and to use available data as much as possible. It was expected that many of the major corridors in the region could be examined within a three-year period.

The ultimate success of this approach to TSM planning depended on both the development of a sound analytic process and the early and continued involvement of local and state agency personnel responsible for project implementation as well as the general public directly affected by travel conditions in the corridor. Direct participation in the studies helped to build a sense of ownership toward the study findings among implementors and the public alike, and this helped the study team to develop acceptable recommendations that had a high probability of implementation.

Corridors and subareas were initially recommended for study by the local jurisdictions and the state highway and transit agencies based on their knowledge of existing travel conditions in their respective areas. An evaluation of these initial recommendations by a committee of RPC, local, and state staff resulted in the designation of a corridor for a prototype study, six major multijurisdictional corridors to be studied by a consultant, and 20 smaller corridors to be subsequently studied by the RPC and the local jurisdictions. The prototype study was initiated by RPC and local staff primarily to test the overall study approach and to establish project management procedures and a meaningful public participation process.

JHK and Associates was selected to perform the six major multijurisdictional studies (1-6). These corridors are diagrammed in Figure 1. The corridors ranged in length from 7 to 20 miles, and the corridor widths were generally limited to the vicinity of the primary radial arterials under study. One corridor included several parallel facilities within a major transportation subarea. JHK developed the detailed analytic approach for the studies, incorporating the project management and public participation processes developed earlier in the prototype. This overall study approach was then used for all subsequent studies by RPC and local staff.

LOCAL INPUT: PROJECT MANAGEMENT AND PUBLIC PARTICIPATION

JHK and Associates was responsible for designing and carrying out the technical analysis for the corridor studies. In addition to working from data gleaned from its own observations and the results of previous studies, JHK took full advantage of the information and advice offered by technicians and citizens versed in the transportation problems and resources of each study area.

Technical and policy guidance for each corridor study was provided throughout by a project management committee (PMC). The PMC consisted of transportation planners and engineers from each of the participating jurisdictions as well as technical staff from relevant state agencies. A typical project management committee roster is outlined below:

1. Local transportation planning, traffic engineering, and air pollution control departments;
2. Planning and Operations Sections of the Maryland Mass Transit Administration (MTA);
3. Office of Planning and Preliminary Engineering of the Maryland State Highway Administration (SHA);
4. Planning Department of the Maryland Department of Transportation;
5. Maryland Air Management Administration of the State Department of Health and Mental Hygiene;
6. Transportation Planning Division of the RPC; and

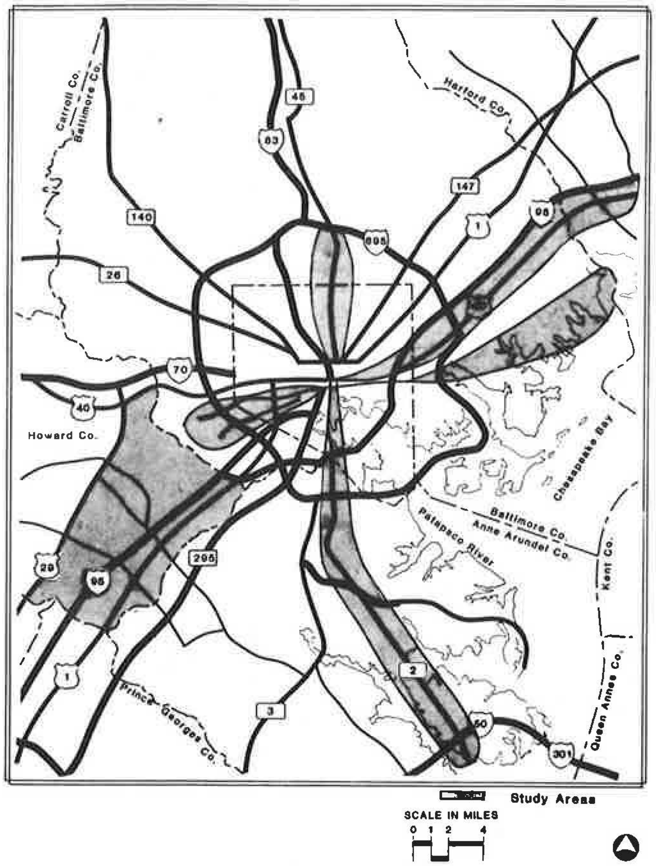


Figure 1. Arterial TSM studies.

7. Regional Air Quality Task Force (RPC advisory committee on the TCP).

Given the multijurisdictional and multimeasure approach of the studies, the PMC meetings provided a particularly important forum for the exchange of views and cooperative decisionmaking among the various agencies involved.

PMC meetings were supplemented with localized technical meetings that focused on the characteristics of the corridor within each jurisdiction. A typical corridor under study might begin in a densely populated urban area, continue through commercial strip development, and terminate along a major thoroughfare in a rural setting. At these meetings, jurisdictional staff were usually the key source for much of the necessary technical data and provided valuable understanding about the local process for implementing projects.

The study approach also included a process for obtaining input from people who lived and worked in the study area. Because the corridor studies emphasized local transportation problems, it was considered essential to the study to involve people who experienced day-to-day travel conditions in the corridor.

Public participation was built into the work program at two critical points. The first round of community meetings was designed to assist in identifying transportation problems, opportunities, and potential actions. The input received at these meetings was used to refine the preliminary list of recommendations and to discover additional problems that had not been previously addressed. The second round of meetings was held to subject the study findings to citizen critique. The citizens' responses were used to determine whether the proposed actions adequately and feasibly addressed community transportation problems and needs. At the end of the study, final reports were made available at library branches and a special "popular" summary report was distributed directly to the citizens who had participated.

Staff from each of the participating jurisdictions took responsibility for initiating local publicity, communicating with interested individuals and groups, and organizing public meetings in their section of the corridor. Other members of the study team attended these meetings, but the local planners took the lead in public involvement activities because of their familiarity with the community and their ability to tailor the process accordingly.

In Baltimore City, where a cadre of "district planners" maintain ongoing connections with the numerous community organizations, public discussion of the corridor studies took place at the regular monthly meetings of interested groups. Other jurisdictions held special meetings open to the general public. Local transportation advisory boards, where they existed, were also involved in the study. Elected officials were kept apprised through periodic briefings.

Community meetings and the study in general were publicized through a variety of channels. These included press releases, which sometimes generated substantial newspaper feature stories or television news coverage; articles in the newsletters of key community or business organizations; and brochures and announcements that were distributed through the mailings of these same organizations as well as through merchants, employers, park-and-ride lots, libraries, and other available means.

In summary, the project management and public participation processes complemented the analytic work and were essential components of the overall study approach.

ANALYTIC APPROACH

The corridor studies were approached through a series of analytic activities. These activities included the definition of study goals and objectives, the identification of problems and opportunities in the corridor, and the selection of alternative TSM actions. The alternatives were then evaluated against each of the project objectives before recommendations were made for project implementation.

A set of goals and objectives was developed prior to the initiation of the corridor study. These goals and objectives were used to guide each step of the study process. Three major goals were identified:

1. Reduce air pollution,
2. Reduce energy consumption, and
3. Improve the efficiency and productivity of the transportation system.

These goals placed a heavy emphasis on the environmental impacts of the TSM actions. Improving transportation system efficiency and performance, while emphasizing improved mobility within the corridor, often supported the air quality and energy goals.

Associated with these goals were the following specific objectives:

1. Reduce air pollution emissions,
2. Reduce vehicle miles of travel (VMT),
3. Increase transportation system productivity,
4. Reduce delay and travel time,
5. Reduce energy consumption,
6. Improve system safety,

7. Promote desirable and minimize undesirable social and economic impacts of transportation improvements,
8. Spend monetary resources in the most cost-effective manner, and
9. Implement actions that are compatible.

Several technical tasks formed the basis of the study approach as diagrammed in Figure 2. These tasks included the following:

1. Perform preliminary activities (e.g., define study area, establish schedules, and determine groups),
2. Identify corridor problems and opportunities,
3. Identify alternative TSM-TCP actions,
4. Evaluate alternative TSM-TCP actions,
5. Recommend TSM-TCP actions, and
6. Prepare final report.

These tasks were documented in a series of technical memoranda (7-13).

ACTIONS CONSIDERED

As the corridor problems and opportunities (task 2) were being identified, a list was made of specific TSM actions to correct these situations. These alternative actions ranged from minor, low-cost improvements to major reconstruction projects or policy changes. Emphasis was placed on selecting those alternatives that could reasonably be expected to meet the primary objectives of the study in a cost-effective manner. The methodology used to identify problems and opportunities and to select possible actions combined a technical analysis of available transportation data, extensive field investigations, meetings with area citizens, and several interviews with key local and state agency personnel.

The types of actions that were considered are listed below and cover a wide spectrum of TSM improvements:

1. Transit programs--Bus route and schedule changes, express bus service, transfer improvements, marketing, bus stop changes, and bus turnouts;
2. Traffic operations and signalization--Intersection and roadway improvements, lane use restrictions, one-way streets, intersection signal improvements, reversible lanes, route diversion techniques, and corridor surveillance and control;
3. High-occupancy-vehicle priority treatments--High-occupancy-vehicle lanes, park-and-ride lots, bus signal priority, priority parking spaces and rates, and automobile-restricted zones;
4. Ridesharing--Employer-based carpool-vanpool matching program, residential-based carpool-vanpool matching program, and transit pass subsidy;
5. Parking management--Curb parking restrictions, off-street parking restrictions, residential permit parking program, and parking rate changes;
6. Commercial vehicle programs--Loading zone management, peak-period on-street loading prohibitions, and truck route designation; and
7. Bicycle and pedestrian treatments--Bicycle lanes, bicycle storage facilities, pedestrian crosswalks and signalization, and pedestrian malls.

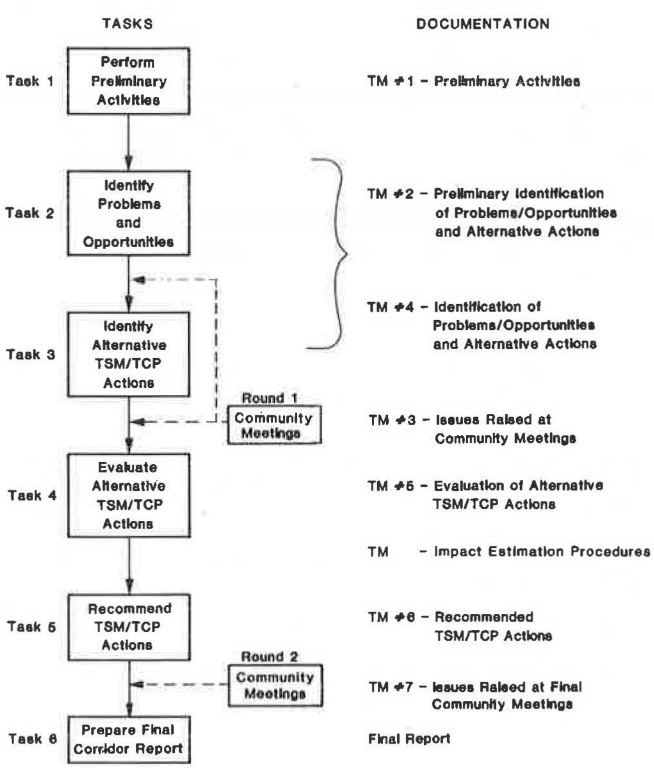
These alternatives included actions aimed at improving overall vehicle movement (e.g., traffic operations and signalization) as well as actions primarily oriented toward improving the mobility of people (e.g., transit programs, high-occupancy-vehicle priority treatments, and ridesharing). Other actions such as parking management, commercial vehicle programs, and bicycle and pedestrian programs served multiple objectives, including the enhancement of residential and commercial areas.

As described above, the possible TSM actions selected for analysis responded to both specific corridor problems and opportunities. Problems were related to deficiencies in transportation service and safety. They included congestion points, locations with a high incidence of accidents, unreliable transit services, excessive truck movements, inadequate bicycle and pedestrian facilities, and inefficient parking patterns. Opportunities, on the other hand, focused on ways to enhance available services. For instance, high employment and residential densities were identified as potential ridesharing targets. Similarly, several locations were identified as possible sites for new park-and-ride lots.

A description of each corridor problem or opportunity with the associated TSM actions and a map depicting locations were prepared for discussion with the PMC and the community. Examples from the MD-2 corridor (8,10) are shown in Figures 3 and 4.

It was soon determined that many problems and opportunities could be best addressed with combinations of TSM actions. As a result, some packaging of TSM actions occurred early in the analysis. Because packaging generally strengthened the positive qualities of each individual action, this strategy enabled a wider variety of actions to be considered.

Figure 2. Corridor study process.



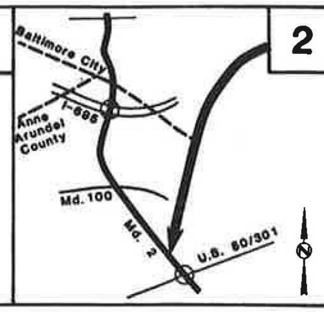
EVALUATION OF ACTIONS

To ensure that each action was evaluated in relation to the key study objectives, a set of 27 specific measures of effectiveness (MOEs), or criteria, was developed. The MOEs, given in Table 1, were selected as the most appropriate indicators of how well each action fulfilled the objectives.

The evaluation process included two elements: impact estimation and comparison of impacts. Impact

Figure 3. Example of identification of problems and opportunities and TSM actions.

MD. 2 CORRIDOR



LOCATION : MD 2 and College Parkway

PROBLEM / OPPORTUNITY :

Intersection congestion

DESCRIPTION OF PROBLEM / OPPORTUNITY :

- Residential development and Anne Arundel Community College generate congestion during both peak periods. Expansion of the residential areas around Cape St. Clair is anticipated to exacerbate the problem. During the spring and summer College Parkway also receives heavy recreational traffic.

ALTERNATIVE TSM/TCP ACTIONS :

- Intersection improvements to include:
  - .. Extending RT lane from WB College Parkway to NB MD 2
  - .. Extending double LT lane from SB MD 2 to EB College Parkway
  - .. *Coordinating signals at MD 2/College Parkway and College Parkway/ Peninsula Farm Rd. to accommodate EB traffic*

    OR

  - .. *Coordinating signals at MD 2/College Parkway and College Parkway/ Peninsula Farm Rd. to accommodate WB traffic.*

Comments :

Figure 4. Locations of problems and opportunities.

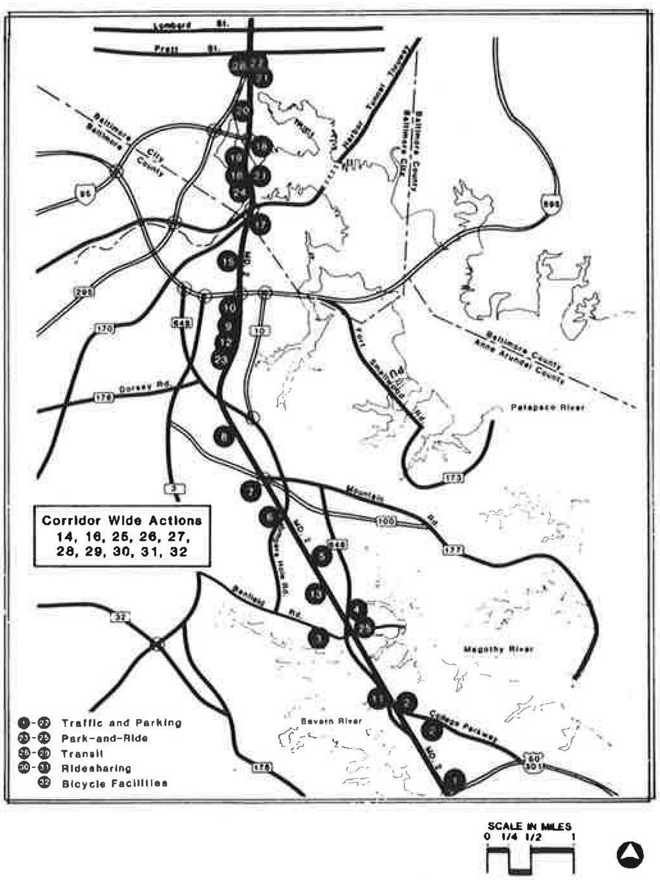


Table 1. MOEs used in TSM-TCP evaluations.

Category	MOE	Unit
Air quality	Changes in HC, NO_x, and CO	Kilograms per day
Energy	Changes in fuel consumption	Gallons per day
Transportation system productivity	Changes in VMT	Vehicle miles per day
	Changes in modal split	Bus riders per day and carpools per day
	Changes in vehicle occupancy	Occupants per vehicle
Transportation system efficiency	Changes in travel time	Minutes per vehicle
	Changes in speed	Miles per hour
	Changes in delay	Seconds per vehicle
	Changes in level of service	Vehicle hours per day
	Changes in vehicle hours of travel	Vehicle hours per day
Safety	Changes in system safety	Descriptive
Cost	Capital cost	Dollars
	Operating cost	Dollars per year
	Total annualized cost	Dollars per year
Cost-effectiveness	Cost per emission change in HC, NO_x, and CO	Dollars per kilogram
	Cost per change in fuel consumption	Dollars per gallon
	Cost per change in VMT	Dollars per vehicle mile
	Cost per vehicle hour of travel	Dollars per vehicle hour
Social and economic	Social impacts	Descriptive
	Economic impacts	Descriptive
Compatibility	Compatibility with other actions	Descriptive
Implementability	Likely public and/or political reaction	Descriptive
	Implementation process	Descriptive
	Funding source(s)	Agency(s), organization(s)
	Time required for implementation	Months, years

Figure 5. Example display of impacts.

2

CORRIDOR: MD 2

TSM/TCP ACTION: Provide intersection and traffic flow improvements at MD 2 and College Parkway

DESCRIPTION OF ACTION:

Implement intersection improvements to include:

- Extending RT lane merge (at MD 2 and College Parkway) from WB College Parkway to NB MD 2
- Extending double LT lane from SB MD 2 to EB College Parkway

In addition to the above,

a) Coordinate signals at MD 2/College Parkway and College Parkway/Peninsula Farm Rd. to accommodate EB traffic 1/

b) Coordinate signals at MD 2/College Parkway and College Parkway/Peninsula Farm Rd. to accomodate WB traffic 2/

AIR QUALITY

Changes in HC: (Kg/day)	a) - 2.9	b) - 1.2 2/
Changes in NOx: (Kg/day)	a) - 3.9	b) - 1.0 2/
Changes in CO: (Kg/day)	a) -31.9	b) -13.4 2/

ENERGY

Changes in Fuel Consumption: (gal/day)	a) -43.2	b) -15.8 2/

TRANSPORTATION SYSTEM PRODUCTIVITY

Changes in VMT: (veh mi/day)	a) Negligible	b) Negligible
Changes in Mode Split:	a) No Effect	b) No Effect
Changes in Vehicle Occupancy:	a) No Effect	b) No Effect

TRANSPORTATION SYSTEM EFFICIENCY

Changes in Travel Time/Speed:	a) Negligible	b) Negligible
Changes in Delay / Level of Service:	a) -34.4 veh-hr/day	b) -23.5 veh-hr/day 2/
Changes in VHT: (veh hr/day)	a) -34.4	b) -23.5 2/

SAFETY

Changes in System Safety: a) and b) Both options will reduce conflicts between through and turning traffic on MD 2. Negligible change on College Parkway.

COST

Capital Cost: ($)	a) $72,000	b) $60,000 2/
Operating Cost: ($/yr)	a) $ 1,600 (maintain inter-connect)	b) Negligible 2/
Total Annualized Cost: ($/yr)	a) $14,350	b) $10,620 2/

2

COST EFFECTIVENESS

Cost*/Emission Change: ($/kg)	HC	$190.60
	NOx	$190.60
	CO	$ 17.30
Cost*/Fuel Consumption Change: ($/gal)		$ 13.60
Cost*/VMT Change: ($/veh mi)		High
Cost*/VHT Change: ($/veh hr)		$10.60

SOCIAL AND ECONOMIC

Social Impacts: Negligible

Economic Impacts: Will improve accessibility to industrial parks on Patuxent Range Road.

COMPATIBILITY

Compatibility with Other Actions: Compatible with all actions, particularly Action #1.

IMPLEMENTABILITY

Likely Public / Political Reaction: Expected to receive positive reaction from truckers. Other reaction should be minimal.

Implementation Process: Include in State (SHA) capital program. Probably not a separate CIP project.

Funding Source(s): State (SHA); possible contribution from industrial park

Time Required for Implementation: 1 to 2 years.

COMMENTS

1/ The analysis of the phasing at this intersection indicated that a separate SB LT phase is not necessary to accommodate this movement. At the same time, total intersection delay would increase if a separate phase were implemented.

Coordination of this signal with Baltimore Street could feasibly be implemented along with Action #1, although this impact was not evaluated.

*= Total Annualized Cost

estimation was performed by using analytic tools that were appropriate for the evaluation of the specific types of TSM actions listed above. In most cases, state-of-the-art "quick response" analysis methods were combined with localized knowledge of the corridor to produce realistic assessments of the impact of each action. A technical memorandum was prepared that documented the impact estimation procedures (14).

Figure 5 shows a typical form used to display the impacts for the TSM actions being considered in a corridor (11). One evaluation sheet was prepared for each alternative action. The number in the corner of the form was keyed to the locations on the map shown previously in Figure 4. This allowed jurisdictional members of the PMC to assess quickly the potential impacts for their respective jurisdictions.

The second element of the evaluation task was to compare the impacts. A two-tiered analysis was performed. First, each action was reviewed for technical impacts. Pursuant to the primary goals of the study, emphasis was placed on the air quality, energy, and transportation efficiency impacts. In most cases, these three goals complemented each other. In some cases, other technical impacts were key factors in the evaluation. For instance, some actions that showed negligible environmental or mobility improvements but produced significant safety improvements were given a favorable evaluation. Conversely, some actions that were expected to degrade safety were placed lower in the final evaluation even though they exhibited good environmental or mobility impacts.

Once the technical review was completed, a critical examination was made of the degree to which the action met the institutional objectives. The key institutional objectives were those that pertain to cost and implementability. In most cases, the cost of the action had a direct bearing on its implementability, and in several cases these two factors overshadowed the technical impacts. In particular, cost was carefully scrutinized in light of the decreasing funds available for implementation of these kinds of actions.

To provide some comparisons between the technical and fiscal impacts, the cost-effectiveness of each action was analyzed. Cost-effectiveness was most useful for assessing more expensive actions in order to determine whether or not the level of expenditure was justified. The remaining objective, compatibility, was a major factor in the comparison of packages of actions.

MOE ratings for each alternative action were presented in a comparative format, as given in Table 2 (12). These ratings condensed the detailed impact information found in Figure 5 and assisted in the formulation of recommendations. The ratings also permitted packages of actions to be concisely evaluated across a wide range of impact areas.

PACKAGING OF RECOMMENDED TSM ACTIONS

The TSM actions recommended were the direct result of the impact evaluation. The findings of the technical and institutional evaluations resulted in a prioritized list of TSM actions and packages.

Packaging was considered essential for several reasons:

1. Some individual actions produced negligible impacts in relation to the project objectives; however, by packaging several actions, the combined impact was often more significant. For example, expanded express bus service in the MD-2 corridor indicated small ridership impacts as an individual action. However, when packaged with park-and-ride lots, the express bus service became more attractive.
2. Many TSM actions, such as traffic signal or transit service improvements, would be largely "invisible" to the public and might fail to gain the

Table 2. Example comparison of TSM-TCP actions.

			MOE											
Action No.	Location	Action	Air Quality	Energy	Cost	Cost-Effectiveness	Productivity	Efficiency	Safety	Social-economic	Compatibility	Implementability	Priority Level	Reason for Priority Level
1	MD-2/US-50/301	Improve signs and lane markings	o	o	+	+	o	+	++	o	+	+	1	Low cost; very good safety benefits; good compatibility with other actions
2a	MD-2/College Parkway	Provide intersection and traffic flow improvements	+	+	-	o	o	+	+	o	+	+	1	Moderate air quality, energy savings, and cost-effectiveness; slight safety improvement; high capital cost
2b	MD-2/College Parkway	Provide intersection and traffic flow improvements	+	+	-	-	o	+	+	o	+	+	3	Only slight air quality and energy savings; high cost and poor cost-effectiveness
3	Robinson/Benfield	Install traffic signal	-	-	o	-	o	-	++	+	+	+	2	In spite of negative air quality impacts, offers very good safety benefits at moderate cost
4	MD-2/Robinson/MD-648	Provide intersection improvements	+	o	o	-	o	+	++	o	+	+	2	Moderate air quality and energy improvements; good safety benefits; moderate cost
5	MD-2/Pasadena	Provide intersection improvements	+	o	o	o	o	+	+	o	+	+	2	Slight air quality and energy improvements; good system efficiency and safety benefits; moderate cost
6	MD-2/Jumpers Hole	Provide intersection improvements	+	o	-	-	o	+	o	+	+	+	2	Slight air quality, energy, and efficiency improvements; good compatibility with other actions; relatively high cost

Note: + = favorable, ++ = very favorable, o = negligible or average, and - = adverse or poor.

support necessary for implementation. Packaging these actions with higher-visibility projects such as improved intersection geometrics or bus stop amenities often improved their chances of being carried out.

3. The costs involved in undertaking groups of similar projects in a given location were considered to be less in some cases than the costs of implementing each action separately.

4. Packaging provided a convenient means of categorizing actions for inclusion in a capital improvement program.

To produce realistic packages of recommendations, three priority levels of actions were identified:

Priority Level	Definition
1	Highly recommended
2	Recommended if additional funds are available
3	Not recommended

Priority level 1 included those actions that were recommended for implementation. These actions were generally those that showed favorable mobility, energy, and air quality impacts, a good cost-effectiveness value, and reasonable implementability. Priority level 2 actions were those that typically showed negligible or, in some cases, adverse mobility, energy, or air quality impacts but that favorably met other objectives such as improving safety or social and/or economic conditions. Some priority level 2 actions showed moderate air quality improvements or energy savings but were costly and thus produced poorer cost-effectiveness values. These were also considered to be more difficult to implement because of budget constraints. Priority level 3 actions were those that were not recommended for implementation. The three priority levels were shown in the evaluation results (Table 2).

The result of the evaluation was a set of recommended TSM packages. Within priority levels 1 and

Table 3. Example of recommended TSM-TCP actions.

TSM/TCP Package	Action No.	Action	Priority Level	Primary Implementing Agency: Baltimore City	Ann Arundel County	State: SHA	MTA	Cost: Capital ($)	Operating ($/year)	Package Impact Emissions (kg/day): ΔHC	ΔNO_x	ΔCO	ΔFuel
Traffic operations	1	Improve signs and lane markings at MD-2/US-50/301	1			x		4 000	*	-0.4	-0.5	-5.5	-3.0
		Provide intersection and traffic flow improvements at MD-2/College Parkway	1		x	x		72 000	1 600	-2.9	-3.9	-31.9	-43.2
		Install traffic signal at Robinson Road/Benfield Road	2		x			30 000	3 000	+3.8	+6.2	+40.4	+46.9
		Provide intersection improvements at MD-2/Robinson Road/MD-648	2			x		50 000	*	-1.0	-0.8	-10.5	-11.7
		Provide intersection improvements at MD-2/Pasadena Road	2		x			25 000	*	-0.6	-0.9	-6.2	-8.9
		Provide intersection improvements at MD-2/Jumpers Hole Road	2		x	x		80 000	*	-0.6	-0.5	-6.0	-7.4
		Improve signs and lane markings at MD-2/MD-100	1			x		40 000	*	-0.7	-0.8	-9.8	-4.1
		Provide intersection improvements at MD-2/Aquahart Road	1			x		100	*	*	*	*	*
		Provide intersection improvements at MD-2/Burwood Avenue/New Ordnance Road	1		x	x		37 000	*	-3.5	-2.5	-40.2	-45.8
		Provide traffic safety improvements at MD-2/MD-648 connector north of College Parkway	2			x		75 000	*	-2.0	-2.8	-28.9	-21.9
		Provide intersection improvements along Hanover Street north of Patapsco River Bridge	1	x				8 000	5 000	-1.6	-1.3	-16.6	-18.9
		Improve directional sign messages along MD-2 within Baltimore City	1	x				1 000	*	*	*	*	*
Subtotal			1					428 000	12 700	-123.6	+36.4	-1517.9	-1720.3
			2					440 000	3 000	-0.7	+0.5	-26.5	-17.8
Total package								868 100	15 700	-124.3	+36.9	-1544.4	-1738.1
HOV priority treatments	9	Improve signing for Glen Burnie park-and-ride lot	1				x	1 000	500	-0.2	-0.5	-2.3	-8.1
	21	Provide parking lot improvements at Hanover Street park-and-ride lot	1	x			x	6 700	+7 030	-0.4	-1.1	-5.3	-18.6
	31	Establish and promote park-and-ride lots using off-street locations	1		x	x	x	206 450	+9 400	-4.3	-12.1	-56.9	-198.1
Subtotal			1					214 150	+15 930	-4.9	-13.7	-64.5	-224.8
Total package								214 150	+15 930	-4.9	-13.7	-64.5	-224.8

Note: * = negligible.

Table 4. TSM corridor study results.

Corridor	No. of Recommended Actions[a]	Mobility Impact		Energy Impact (gal/day)	Air Quality Impact (kg/day)			Capital Cost ($000s)	Operating Cost[b] ($000/year)
		VHT per Day	VMT per Day		HC	NO_x	CO		
1	26	1 879	54 183	2 642	70	158	896	1800	-35
2	28	2 795	79 144	3 527	99	202	1262	2500	+286
3	14	1 490	44 000	2 385	68	154	843	1900	-4
4	19	2 680	89 890	4 371	102	270	1324	790	+18
5	32	5 564	87 803	5 797	227	245	2896	1253	+55
6	15	4 862	158 220	7 048	169	428	2167	1340	+123
Total	134	19 270	513 240	25 770	735	1457	9388	9583	+443

[a]Total of priority level 1 and 2 actions. [b]+ = net annual cost; – = net annual cost savings.

2, the actions were grouped by functional category (e.g., traffic operations and parking, ridesharing, etc.) and by primary implementing agency. Several agencies often shared responsibility for implementing a particular TSM action or package.

Table 3 gives a selection of the TSM actions recommended for the MD-2 corridor (12). In addition to displaying the packaging of actions, priority level, and primary implementing agencies, Table 3 gives the key financial (capital and operating) and environmental (air quality and energy) impacts. The impacts for each package were subtotaled for each priority level and then summed for the total package. This format provided each implementing agency with a clear indication of its responsibilities as well as the impacts to be expected of each recommended TSM action.

STUDY RESULTS

These studies showed that TSM actions can provide substantial transportation and environmental improvements along arterial corridors. Table 4 summarizes the expected impacts for all recommended actions in the six corridors studied. These impacts were found to be significant when compared with other transportation actions in the Baltimore region. For example, the expected 735-kg daily reduction in HC represented more than 15 percent of the region's goal for reducing HC from transportation sources. Together, these corridor improvements could be accomplished at a lower cost than a typical major highway construction project.

The packages of TSM actions each contributed differently to the impacts given in Table 4. The ridesharing packages were found to contribute more than two-thirds of the mobility, energy, and air quality benefits at less than 5 percent of the total cost of all the recommended actions. Traffic operations and parking management actions together constituted roughly half of the total costs while contributing about 20-30 percent of the mobility, energy, and air quality benefits. Transit operational packages, combined with park-and-ride lots, were found to provide 5-10 percent of the benefits at about 25 percent of the costs. Other packages, such as bicycle and pedestrian actions, commercial vehicle programs, and high-occupancy-vehicle priority treatments (exclusive of park-and-ride lots), had relatively low costs but did not contribute significantly to mobility, energy, or air quality benefits in these corridors. However, these actions often fulfilled other social or economic objectives that were important in the evaluation.

CONCLUSIONS

Several conclusions emerged from the TSM corridor studies. The analysis process used in the studies enabled a full range of TSM actions to be identified and evaluated in a cost-efficient manner. The use of standardized presentation formats assisted in the review and comparison of results by technical staff and decisionmakers. The final recommendations were depicted in sufficient detail to enhance the prospects for implementation. Agency responsibilities and costs were specified, and the interactions among projects within various TSM packages were explained.

Overall, the recommended packages of TSM actions were found to be effective in meeting the project objectives of improved air quality, conserved energy, and reduced traffic congestion. In particular, the studies demonstrated that traffic-flow improvements on congested arterials could have positive air quality impacts, which contradicted previous notions that such improvements invariably resulted in more travel and more pollution. The analyses allowed the RPC for the first time to estimate potential regionwide impacts of traffic-flow improvements at alternative funding levels.

The corridor study recommendations were a major source of committed projects for inclusion in the Baltimore region's 1982 TCP. In fact, many of the recommendations are now being implemented or are included in current operating or construction programs. The success of the study approach is further verified by the inclusion of additional corridor studies in the current work programs of several jurisdictions in the region.

Public participation played a vital role in identifying corridor problems and opportunities, in selecting appropriate packages of actions, and in determining the implementability of various alternatives. The public meetings allowed community members to air some longstanding concerns about transportation in the corridor area and to suggest workable alternatives. In turn, the corridor study meetings and accompanying publicity sparked a greater public awareness about the issues being addressed.

Finally, the corridor study process provided a forum in which local, state, and federal agency personnel could meet and discuss TSM projects that require multiple-agency participation. The cooperative project management process, together with public participation efforts, complemented the analytic work and resulted in recommendations that were both better and more likely to be accepted.

REFERENCES

1. JHK and Associates. York Road Corridor Study. Regional Planning Council, Baltimore, MD, Summary Rept. and Final Rept., Jan. 1982.

2. JHK and Associates. Wilkens-Frederick Corridor Study. Regional Planning Council, Baltimore, MD, Summary Rept. and Final Rept., Jan. 1982.
3. JHK and Associates. U.S. Route 40 East Corridor Study. Regional Planning Council, Baltimore, MD, Summary Rept. and Final Rept., Jan. 1982.
4. JHK and Associates. Eastern Avenue Corridor Study. Regional Planning Council, Baltimore, MD, Summary Rept. and Final Rept., Jan. 1982.
5. JHK and Associates. MD. 2 - Ritchie Highway Corridor Study. Regional Planning Council, Baltimore, MD, Summary Rept. and Final Rept., Jan. 1982.
6. JHK and Associates. Baltimore-Washington Subarea Study. Regional Planning Council, Baltimore, MD, Summary Rept. and Final Rept., Jan. 1982.
7. JHK and Associates. Preliminary Activities. Regional Planning Council, Baltimore, MD, Tech. Mem. 1, 1981.
8. JHK and Associates. Preliminary Identification of Problems/Opportunities and Alternative Actions. Regional Planning Council, Baltimore, MD, Tech. Mem. 2, 1981.
9. JHK and Associates. Issues Raised at Community Meetings. Regional Planning Council, Baltimore, MD, Tech. Mem. 3, 1981.
10. JHK and Associates. Identification of Problems/Opportunities and Alternative Actions. Regional Planning Council, Baltimore, MD, Tech. Mem. 4, 1981.
11. JHK and Associates. Evaluation of Alternative TSM/TCP Actions. Regional Planning Council, Baltimore, MD, Tech. Mem. 5, 1981.
12. JHK and Associates. Recommended TSM/TCP Actions. Regional Planning Council, Baltimore, MD, Tech. Mem. 6, 1981.
13. JHK and Associates. Issues Raised at Final Community Meetings. Regional Planning Council, Baltimore, MD, Tech. Mem. 7, 1981.
14. JHK and Associates. Methodologies Used to Estimate Impacts of Alternative Actions. Regional Planning Council, Baltimore, MD, Tech. Mem. 8, Nov. 1981.

Publication of this paper sponsored by Committee on Transportation System Management.

Summary of Operational Characteristics and Anticipated Evaluation of I-66 HOV Facility

K.E. LANTZ, JR., AND E.D. ARNOLD, JR.

In late 1982, the final section of I-66 in the Washington, D.C., suburbs in Northern Virginia was opened to traffic after a lengthy and controversial developmental process. The final product of that process is a four-lane, limited-access, parkway-type facility from which heavy-duty trucks are excluded at all times. Peak-period, peak-direction use is restricted to high-occupancy vehicles (HOVs), emergency vehicles, and vehicles bound to and from Dulles Airport. Finally, to maintain safe and efficient traffic flows on the facility, a comprehensive, computer-controlled traffic management system (TMS) will be installed. Basic elements of the system include closed-circuit television, ramp metering, motorist advisory signing, and interface with adjacent traffic signal systems. The Virginia Department of Highways and Transportation, with funding from the Federal Highway Administration, has undertaken a study of this section of highway. The objective is to evaluate I-66 and the HOV restrictions and the TMS. The results of the study will prove valuable in assessing the merits of the concepts used and in planning projects of this nature. A summary of the history, design elements, operational characteristics, and anticipated evaluation of the final section of I-66 is presented.

The approximately 10-mile-long section of I-66 between the Capital Beltway (I-495) in the Virginia suburbs of Washington, D.C., and the Potomac River was opened to traffic on December 22, 1982 (see Figure 1). Estimated to cost $300 million, the facility is heavily traveled by commuters to and from the nation's capital.

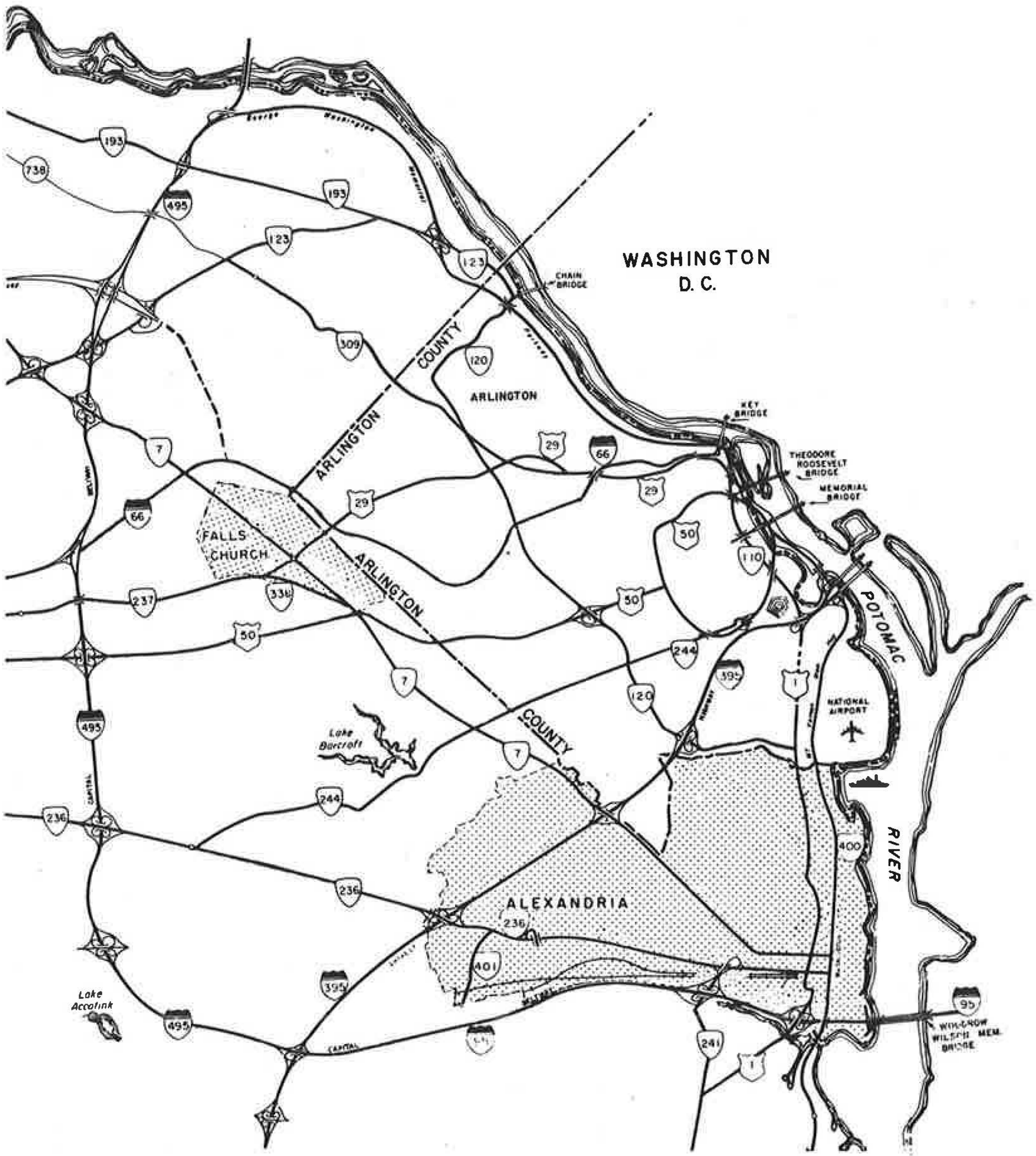
Considerable controversy has surrounded the project, which has evolved into a four-lane, limited-access facility. Heavy-duty trucks are excluded at all times, and high-occupancy vehicles (HOVs)--buses and vanpool and carpool vehicles carrying four or more persons--emergency vehicles, and vehicles bound to or from Dulles Airport are the only vehicles allowed on the facility in the peak direction during peak hours. A detailed plan to enforce these restrictions has been developed. Consideration has also been given to environmental issues in the design of the facility to ensure maximum compatibility with the surrounding area.

In addition, a comprehensive traffic management system (TMS) to control and facilitate the flow of traffic will be implemented by the spring of 1983. The elements of this system include an enforcement plan, ramp metering, closed-circuit television (CCTV), variable message signs, incident detection, lighting, and central control. The system will also be implemented on an existing segment of I-395 that contains the reversible HOV lanes. That segment extends from the vicinity of the Springfield interchange just south of the Capital Beltway to the District of Columbia (Figure 1). Both facilities will be under interim control by the TMS for approximately one year as the various elements are implemented. The TMS should be fully operational by early 1984.

The concepts being incorporated into these sections of I-66 and I-395 represent the most recent technology in traffic control and management and offer the potential for the most efficient use of the facility. Accordingly, the Virginia Department of Highways and Transportation, with funding from the Federal Highway Administration (FHWA), has initiated a study to investigate and evaluate the operation of the section on I-66 and the TMS on both I-66 and I-395.

In light of the national interest in the I-66 facility, this paper has been developed to (a) briefly recount the history of I-66, (b) describe the TMS to be used, and (c) outline the evaluation to be undertaken.

Figure 1. Location map.



HISTORY OF I-66

The planning of I-66 took place during a time characterized by a renewed interest in public transit, development of opposition in urban areas to large-scale freeway projects, and an increased concern for environmental quality (1). As a result, the design of that segment of the highway inside the Capital Beltway evolved from an eight-lane Interstate facility to a four-lane, multimodal corridor that uses state-of-the-art traffic control strategies and technology.

Evolution of Roadway Design

Initial Plans

The need for a high-capacity, east-west road linking Fairfax and Arlington Counties with the District of Columbia was first recognized in a 1938 study conducted by Arlington County. This need was reflected in the local zoning and land use policies adopted over the next 20 years to reserve a corridor for the road. Following creation of the Interstate highway system by the 1956 Federal-Aid Highway Act, this corridor was incorporated into that system.

Delays to Planning

Several developments between 1962 and 1970 delayed the final planning and construction of I-66 east of the Capital Beltway. Among these were the public controversy and litigation surrounding the Three Sisters Bridge/I-266 project that was to connect with I-66 and provide an additional Potomac River crossing. The protracted legal negotiations by local commuters seeking the continued operation of the Washington and Old Dominion Railroad, segments of which were proposed to be used for the I-66 right-of-way, also delayed the project. Finally, additional time was needed to coordinate the planning of I-66 and the Metrorail rapid transit system, since a transit line had been proposed for the median of I-66.

During this same period, new federal legislation and administrative directives were adopted that governed highway planning and construction and that affected I-66 specifically. Enacted in 1966, Section 4(f) of the Department of Transportation (DOT) Act prohibits the approval of projects that use parkland unless there is no "feasible and prudent alternative" to such use. The original I-66 design proposed the taking of portions of several parks for right-of-way. In 1970, Congress enacted the National Environmental Policy Act (NEPA), Section 102 of which requires the preparation of an environmental impact statement (EIS) for major federal actions "significantly affecting the quality of the human environment".

Eight-Lane Concept

In 1968, the Washington Metropolitan Area Transit Authority (WMATA) adopted plans for construction of the regional rail rapid transit system that featured a rail line in the I-66 median. In 1970, public hearings on an eight-lane cross section for I-66 were held. In early 1971, the Arlington Coalition on Transportation, Arlingtonians for the Preservation of the Potomac Palisades, and several individuals filed suit in U.S. District Court, contending that federal and state highway officials had not complied with Section 4(f) of the DOT Act, Section 102 of NEPA, and Section 128 of Title 23 of the U.S. Code, which governs public hearings for highway projects. In October 1971, the District Court dismissed the suit, but on April 4, 1972, the U.S. Court of Appeals for the Fourth Circuit reversed the District Court's decision. The Court of Appeals enjoined further acquisition of right-of-way and construction for the highway until the Virginia Department of Highways and Transportation filed an EIS and determined, pursuant to Section 4(f), that there was no "feasible and prudent alternative" to the use of the parklands. The court also ruled that new public hearings had to be held to consider the social and environmental impacts of the project and the economic effects of the proposed location in light of the planned rapid transit service in the corridor.

In September 1972, the Virginia Department of Highways and Transportation, with FHWA involvement, initiated a study to consider alternatives to the I-66 proposal and to review the various anticipated impacts of the proposed facility pursuant to the decision by the Court of Appeals. The resulting draft EIS/4(f) was released in November 1973.

After consideration of the public hearing comments and the draft EIS, the Virginia Highway and Transportation Commission, on February 21, 1974, adopted a new multimodal facility concept that consisted of an eight-lane cross section with Metrorail in the median.

Six-Lane Multimodal Concept

In September 1974, FHWA requested that the Virginia Department of Highways and Transportation undertake additional efforts to alleviate the impacts of the proposed project. Consequently, the original proposal was modified to reduce the number of lanes from eight to six, and the roadway segment through the Spout Run Parkway area was redesigned. These modifications were submitted to FHWA for consideration by then Secretary of Transportation William Coleman. On August 1, 1975, Secretary Coleman disapproved the proposal.

Four-Lane Multimodal Concept

In response to the decision of the Secretary of Transportation, the Virginia Department of Highways and Transportation and FHWA developed a four-lane multimodal concept (2). A draft supplement EIS/4(f) was completed in June 1976, and public hearings were conducted in mid-July.

On January 5, 1977, Secretary Coleman issued a decision approving construction of I-66 between the Capital Beltway and Rosslyn, subject to the following conditions:

1. Provide, without cost, right-of-way in the I-66 median for construction of a Metrorail line and complete construction of the median to the point that rails can be placed by the WMATA at minimal construction expense;
2. Transfer from Virginia to WMATA funds previously allocated for the construction of I-266;
3. Restrict the use of I-66 between the Capital Beltway and the Potomac River in the peak direction and peak period to buses, carpool vehicles carrying four or more persons, emergency vehicles, and vehicles bound to or from Dulles Airport;
4. Exclude heavy-duty trucks (two axles, six tires, and larger) from the facility at all times;
5. Submit within 60 days a detailed plan for enforcing these traffic restrictions;
6. Do not construct any highway lanes in the right-of-way beyond the four approved;
7. Include design elements and other features intended to minimize and compensate for adverse social and environmental impacts and develop a facility, as far as possible, similar to the George Washington Parkway; and
8. Provide assurances that minorities and minority-owned enterprises will participate in all construction.

Construction of Project

Special Construction Features

Following Virginia Governor Godwin's acceptance of the conditions outlined in Secretary Coleman's decision, the Virginia Department of Highways and Transportation proceeded with the advertisement of the basic roadway construction projects. Construction began in the fall of 1977, and the roadway was opened to traffic in December 1982.

A number of unique practices were used to minimize the disruption caused by construction, including the placement of an information trailer near the project. An on-site environmental monitor was hired to review the contractors' construction practices and suggest corrective measures as needed. Extensive use was made of architectural and landscaping consultants in designing bridges, retaining and noise walls, and other features. A steering committee consisting of citizens from Arlington and Fairfax Counties reviewed the construction plans and made suggestions concerning the design of the roadway.

Multiple use of the corridor right-of-way includes a Metrorail line in the roadway median and a 10-ft-wide parallel bikeway. Surplus right-of-way has been used to create a 4.6-acre linear park, and an additional 10.5 acres will supplement existing parks. At Washington and Lee High School, a parking deck is being constructed over the roadway, and a pedestrian plaza is planned for Rosslyn.

Dulles Access Road Link

In conjunction with the construction of I-66, the Federal Aviation Administration (FAA) is constructing an extension of the Dulles Airport Access Road from its present terminus at VA-123 to I-66 east of the VA-7 interchange. When this segment is completed, traffic going to and coming from Dulles Airport will have a high-speed, limited-access link to downtown Washington, D.C., via I-66 and the Access Road (3).

With completion of the Access Road, traffic with legitimate business at Dulles Airport will be permitted on I-66 at all times. Maintenance of the four-person-occupancy requirement on I-66 for non-airport traffic will require a complex enforcement plan, which is described later in this paper.

Metro Service

During the construction of I-66, provisions have been made within the median to accommodate a Metrorail line. The "K-line" will run at-grade in the I-66 median from its western terminus at Vienna to Fairfax Drive. At Fairfax Drive, Metrorail leaves the I-66 median and continues underground through Arlington Court House, Rosslyn, and across the Potomac.

Four stations are being constructed in the I-66 median: The East Falls Church and West Falls Church Stations are east of the Capital Beltway, and the Vienna and Dunn Loring Stations are west of the Beltway.

Metrorail service as far as the Vienna Station will be initiated in 1986; in the interim, WMATA will operate feeder bus service in the I-66 corridor to the Ballston Station, which is currently the last stop on the K-line.

TRAFFIC MANAGEMENT SYSTEM

Concurrent with the letting of the roadway construction contracts, the Virginia Department of Highways and Transportation contracted with JHK and Associates for the preparation of the traffic enforcement plan required under condition 5 of the Coleman decision. In February 1977, the I-66 Traffic Management Concepts Report was submitted to and subsequently approved by the U.S. Department of Transportation.

The traffic control and management features recommended by the report to achieve these objectives include an enforcement plan, entrance ramp metering, CCTV, electronic surveillance, lighting, and computerized control (4). The report recommended that a similar traffic control system be implemented on Shirley Highway (I-95/I-395) to facilitate integrated traffic control strategies (5).

In April 1978, the Virginia Department of Highways and Transportation contracted with the firm of Howard, Needles, Tammen and Bergendoff, with Sperry Systems as a subconsultant, for the refinement of the traffic management concepts and the development of the plans, specifications, and estimates for their implementation (6). The functions of the elements found on both routes are discussed below.

Enforcement

Management of I-66 will require a complex enforcement strategy with permanent and changeable message signs that advise motorists of the restrictions in effect. A special contingent of state police will be assigned to the road to monitor compliance with the occupancy requirements, truck prohibitions, and ramp metering.

Enforcement areas have been constructed to assist in the identification and citation of violators. West of the Dulles Airport Access Road interchange with I-66, all traffic is subject to the occupancy restrictions, and the pull-offs are located on the main roadway.

East of the interchange, the roadway will be concurrently used during peak periods by Dulles Airport traffic and vehicles subject to the four-person-occupancy requirement. Thus, violators of the occupancy requirement cannot be identified on the main roadway and instead must be apprehended as they attempt to enter or leave I-66 at points other than the interchange. Enforcement areas are located at the I-66 eastbound entrance and westbound exit ramps for this purpose.

A related enforcement issue concerns elimination of commuter traffic that uses the Dulles Airport Access Road in violation of its stated purpose. Currently, eastbound commuters enter the Access Road via a westbound on-ramp, drive to the airport and make a U-turn, and then proceed eastbound to their ultimate destination. Because there is no way to distinguish between legitimate Dulles Airport traffic and "backtrackers" once they are on I-66, the illegal users of the Access Road must be identified before they enter I-66. FAA is studying a number of methods for discriminating between airport users and backtrackers, who constitute up to 50 percent of the peak-period Access Road traffic. The strategies under consideration are areawide electronic surveillance, license plate comparison with selective direct surveillance, and areawide police surveillance. FAA will implement a strategy for eliminating backtracking prior to completion of the Access Road extension to I-66 (7,8).

Ramp Metering

Entrance ramp metering will be instituted on 7 of the I-66 ramps and 20 of the existing I-395 ramps. Under the control of the TMS computer, the series of ramps will be treated as a system; individual metering rates will be set to provide a desired mainline level of service while entrance ramp delay and impacts on adjacent corridor arterials are minimized. Ramps will be placed under control by time of day, and metering will be initiated if the sum of the mainline and ramp demands exceeds a preset threshold. If metering is warranted at one location, it will be automatically initiated at all others in the same direction. Pretimed metering rates and manual override will be available in the event of system failure.

The ramp configurations to be used include standard single lane, high-volume single lane, and dual lane. More restrictive metering will be used at locations with sufficient storage space. All ramps will be equipped with queue spillover detectors. Because heavy Metrobus volumes are anticipated in the I-66 corridor prior to completion of Metrorail to Vienna, two I-66 ramps will have bus-bypass-lane configurations.

CCTV

CCTV will be used in the TMS to monitor ramp-metering operations and roadway use. Other applications include the observation of incidents, the verification of variable-message sign texts, and the confirmation of alarms generated by the detector-based systems.

Continuous surveillance will be provided on I-395 by 25 cameras mounted on high-level poles (approximately 50 ft in height) at 0.5-mile intervals. On I-66, the initial installation of 10 cameras will permit surveillance of the interchanges. Spare capacity for 9 additional cameras will be built into the system to permit continuous surveillance. At the control center, one monitor will be provided for each camera and video recorders will be used to retain the television images.

Variable-Message Signs

Disc-matrix variable-message signs will be placed at 9 locations on Shirley Highway and 19 locations on I-66 and on the major approach roads to both routes. The signs will be used to display regulatory information with respect to ramp metering and HOV use. In the event of major delays, advisory and route guidance information will be displayed on the signs located at the route selection decision points.

Incident Detection

Automatic vehicle surveillance and incident detection will be accomplished by using pavement induction loops located at half-mile intervals throughout both highways. The system will be used to determine existing traffic conditions, develop short-term predictions of variations from present conditions, and implement appropriate control strategies such as ramp control and motorist advisories in the event of major incidents. Other applications include providing system evaluation by means of various on-line measures of effectiveness and developing an historic data base for use in updating system parameters and for studies and planning.

Two incident detection arrangements will be used, depending on the volume of traffic. During periods of heavy to moderate flow, the detectors will continuously monitor the traffic density at each station. In the event that the detectors sense an increase in density at one location and a corresponding decrease at a downstream location, an alarm will be sounded at the control panel and an incident status page will be displayed on the control console CRT. Using CCTV, the operator will confirm the incident and implement the appropriate response mechanism.

During periods of light flow, information on incidents will be relayed to the control center by police on patrol, citizens band radio, etc. The system operator will enter the information into the system, view the appropriate television monitor to confirm the incident, and implement the response.

Once incidents have been detected and confirmed, the central control computer's advisory sign algorithm will determine the message to be displayed. Message selection can occur automatically as a function of currently measured traffic conditions or manually by operator intervention.

Direct radio and telephone links between the control center and state and local police, fire and rescue services, maintenance personnel, and towing companies will ensure quick response to incidents and short clearance time. Information concerning the incident will also be provided to local radio and television stations.

Lighting

The need for lighting and the type of lighting to be used on I-66 were established only after considerable study. Continuous roadway lighting will be provided to maintain safe and efficient traffic flows, to aid in the identification and removal of incidents, and to support the surveillance and control system.

On I-66, mainline lighting will be provided by 250-W, high-pressure sodium luminaires mounted in offset fixtures on 45-ft poles. The poles will be spaced 326 ft apart and set back 30 ft from the edge of the pavement. Lighting will also be provided on the I-66 bikeway, where 150-W, high-pressure sodium fixtures will be mounted on 15-ft poles at 165-ft intervals. On Shirley Highway, the existing mercury vapor luminaires will be replaced with high-pressure sodium fixtures to achieve lower lighting costs and increased illumination.

Central Control

Operation of the TMS will be based in a two-story building located on Virginia Department of Highways and Transportation property on Columbia Pike. Control equipment housed in the building will include a central processing unit, disk memories, a keyboard-printer, interactive CRT terminals, a card reader, a line printer, and magnetic tape drives. System operators will monitor a console consisting of panels for map control, video control, alarm and system control, camera control, and sign control.

Behind the console, a dynamic map display will use color-coded, computer-driven lamps to indicate the status of each detector station, metering signal, television camera, and variable-message sign. The map will also be capable of displaying the volume, density, and speed of traffic at each detector station.

The control configuration will consist of microprocessors at each roadside cabinet and a high-performance computer at the control center. Operator input may be through either the control panel or the CRT; those functions that require rapid operator response are incorporated in the control panel.

The center will be staffed by a systems engineer, two operators, two technicians, and one secretary. The contract for the system includes the development and administration of appropriate training courses for these personnel.

The system is designed to transmit and receive real-time data from the signal system control computers located in the adjacent jurisdictions.

Public Information Program

To familiarize the public with the operation and benefits of I-66 and the I-66/I-395 TMS, the Virginia Department of Highways and Transportation, with the cooperation of persons coordinating ridesharing in the neighboring localities, has developed an educational and promotional campaign.

The goals of this program are to (a) inform motorists of the restrictions in effect on and the proper use of I-66 and I-395, (b) provide information on the operation and the positive attributes of the TMS, (c) supply accurate and timely materials to the media and the public so as to encourage further dissemination of information, and (d) encourage participation in existing and proposed ridesharing programs. Elements of the program will include a slide-tape presentation, newsletters, a call-in television program, free-standing exhibits, pamphlets, and radio and television spot announcements.

EVALUATION OF I-66 HOV FACILITY

In recognition of the uniqueness of the I-66 facility, the controversy surrounding its development, the modern technology involved, and the expected national interest in its operation, the Virginia Department of Highways and Transportation, with funding from FHWA, has initiated a study to evaluate the I-66 HOV facility and the TMS on I-395. This section of the paper describes the purposes and objectives of the study, the schedule for the study as governed by the I-66 project schedule, the data to be collected, and the anticipated analyses.

Study Objectives

Within the framework of the two goals of the study--evaluation of I-66 and the HOV restrictions and evaluation of the TMS--the following specific objectives were established:

1. Evaluate the operating characteristics of I-66 by determining (a) the use of the facility by automobiles, public transportation, bicycles, and pedestrians and (b) the efficacy of the enforcement plan in managing the truck restrictions, the peak-hour and peak-direction restrictions, and the ramp metering;
2. Evaluate the impacts of the opening of I-66

Table 1. General data requirements and period of data collection for each study objective.

Study Objective	Volume	Speed and Delay	Occupancy	Accidents	Neighborhood Attitude Survey	I-66 Transit and Carpool Survey	Modal Split	Survey of Bicyclists and Pedestrians	Incidents	Enforcement	Miscellaneous
Determine use of I-66	D	-	D	-	-	D	D	D	-	-	-
Determine effectiveness of enforcement plan on I-66	-	-	-	-	-	-	-	-	-	D/A	-
Determine changes in regional traffic patterns	B/D	B/D	B/D	-	-	-	B/D	-	-	-	-
Determine impacts of ramp metering on local streets	B/D/A	-	-	-	-	-	-	-	-	-	D/A
Determine environmental impacts	B/D	-	-	-	D	-	-	-	-	-	D
Determine reactions of media, local officials, and the public	-	-	-	-	D	D	-	-	-	-	D/A
Determine effectiveness of marketing and public information	-	-	-	-	D	D	-	-	-	D/A	D/A
Determine levels of safe, efficient traffic flows on I-66 and I-395	D/A	D/A	-	D/A	-	-	-	-	-	-	D/A
Determine effects of TMS on I-395	B	B	-	B	-	-	-	-	-	-	-
Determine efficiency with which incidents are detected and managed on I-66 and I-395	-	-	-	-	-	-	-	-	D/A	-	D/A
Determine effectiveness with which central control facility operates	-	-	-	-	-	-	-	-	-	-	D/A

Note: B = before opening of I-66, D = during interim control by the TMS, and A = after final control by the TMS.

and the improvements to I-395 by determining (a) the changes in regional traffic patterns, (b) the impacts of ramp metering on local streets, and (c) the impacts on energy consumption and air, noise, and light pollution;

3. Evaluate the local response to the opening of I-66 and the improvements to I-395 by determining (a) the reaction and attitude of the media, local officials, and the general public and (b) the effectiveness of the marketing and public information efforts; and

4. Evaluate the performance of the TMS on I-66 and I-395 by determining (a) the levels at which safe and efficient traffic flows are maintained, (b) the effects of the TMS on the operational characteristics of I-395, (c) the efficiency with which incidents are detected and managed, and (d) the level of effectiveness at which the central control facility operates.

Study Schedule

As suggested in the introduction to this paper, three periods of project development can be identified: (a) before the opening of I-66, (b) after the opening of I-66 but during interim control by the TMS, and (c) after final control by the TMS.

Data needed before the opening of I-66 were collected in the fall of 1982. To achieve the objectives of the study concerned with the evaluation of I-66 and the HOV restrictions and to discount seasonal variations, a second round of data collection is scheduled for the fall of 1983. Data for which seasonal variation is not a factor will probably be collected as soon as it is judged that traffic patterns have stabilized after the opening of I-66. A report will be prepared to document the findings of the first two rounds of data collection.

To attain the objectives concerned with the evaluation of the TMS and again to discount seasonal variation, a final round of data collection will be needed in the fall of 1984. A report that documents the findings concerning the TMS will be prepared.

Data Required for the Study

Table 1 summarizes the information to be collected for each objective. A description by study objective of the data to be collected or developed is given below.

1. Use of I-66--Volume, modal split, and occupancy data will be collected in the fall of 1983. A questionnaire survey of carpool, vanpool, and bus users will also be conducted, probably in the spring of 1983. Finally, counts will be made of the number of bicyclists and pedestrians using the bicycle trail.

2. Effectiveness of enforcement plan on I-66--Costs, personnel and equipment requirements, and the number of citations associated with the enforcement plan on I-66 will be obtained along with qualitative information concerning methodology, problems, changes, etc. Enforcement information will be collected during interim control and after final control by the TMS.

3. Changes in regional traffic patterns--Before-and-after volume, modal split, and occupancy data will be collected at 34 stations in Northern Virginia during the fall of 1982 and 1983. In addition, speed and delay data will be collected along all major radial commuter routes. The routes are located clockwise from VA-1 in the east to the George Washington Parkway in the north. Stations are located along these routes and range from sites outside the Capital Beltway to the Potomac River bridges.

4. Impacts of ramp metering on local streets--On-ramp volumes will be collected before implementation of the TMS on I-395 and during interim and final control by the TMS on both I-395 and I-66. Qualitative information concerning problems experienced at the metered ramps will also be obtained. Finally, a field inspection of each metered ramp in peak-period operation will be undertaken if deemed necessary.

5. Impacts on the environment--In addition to measuring fuel consumption and emissions on I-66, overall changes in the environs will be calculated from the before-and-after data. In addition, information on noise and light pollution will be obtained through a survey of neighborhoods adjacent to I-66 and from newspapers, citizens' groups, complaints, etc.

6. Reaction of media, local officials, and the public--Information on local reaction to the opera-

tion of and concepts involved in the highway improvements will be obtained through the I-66 user and neighborhood surveys, newspapers, citizens' groups, complaints, possible legal challenges, institutional problems, etc. This information will be collected throughout the study.

7. Effectiveness of marketing and public information--Information on the effectiveness of the marketing and public information campaign to inform the public of the operational characteristics of I-66 will be obtained from the I-66 user and neighborhood surveys, the level of compliance with the operating restrictions, and newspapers, citizens' groups, complaints, etc. This information will be collected throughout the study.

8. Safe and efficient traffic flows on I-66 and I-395--Traffic-flow conditions will be determined from the volume-to-capacity (V/C) ratios and speed and delay data on I-66 and I-395 during interim control and after final control by the TMS. Safety will be determined through the collection of accident data on both facilities throughout the last two periods of project development. Finally, qualitative information concerning the performance of the TMS elements will be obtained.

9. Effects of TMS on I-395--Unlike I-66, which is a new facility, the segment of I-395 on which the TMS will be installed is an existing roadway; therefore, a "before TMS" phase exists. Accordingly, V/C ratios, speed and delay data, and accident data were collected for I-395 in the fall of 1982.

10. Incident detection and management on I-66 and I-395--Information for interim and final TMS control concerning the detection of, response to, and management of incidents on the facilities during the week will be generally qualitative; however, elapsed time between the incident, detection, response, and management of the incident will be obtained where possible. Again, qualitative information on the performance of the TMS elements will be obtained.

11. Operation of the central control facility--Qualitative information for interim and final TMS control will be used to evaluate the control center's operation. Items such as repair records, repair costs, operating costs, and equipment failures will be documented when possible.

Anticipated Analyses

Following is a description by study purpose of the major analyses to be undertaken initially. As the study progresses and these analyses are performed, there may be a need for additional analyses.

Operating Characteristics of I-66

A description of the use of I-66 will be developed. In addition to determinations of daily, peak-period, and peak-hour traffic volumes, profiles of hourly volumes will be developed for the average weekday, Friday, Saturday, and Sunday at four stations along the facility. The profiles will also be developed for the on-ramps. The modal split between automobiles and buses will be determined for the morning and evening peak periods and peak hours at the four stations. In addition, automobile and transit occupancy rates will be calculated for each of the two peak periods and peak hours. A summary of the use of the bicycle trail will be developed from counts at five locations. Finally, a questionnaire survey of peak-period carpoolers, vanpoolers, and transit riders will make it possible to develop a profile of the I-66 user, including socioeconomic characteristics, trip characteristics, prior mode and route used, and opinions on unique aspects of the roadway.

Impacts of I-66

Changes in regional traffic patterns for an average weekday will be evaluated by comparing peak-period and peak-hour volumes, modal split, and occupancy at 34 stations located along 11 major radial commuter routes before and after the opening of I-66. In addition, before-and-after travel speeds along these radial routes will be compared. Before-and-after volumes at the on-ramps to both I-66 and I-395 will also be compared to determine possible diversion and impacts on local streets caused by ramp metering.

Finally, environmental impacts will be measured by calculating before-and-after emission and fuel consumption statistics at the 34 stations or along the radial routes, as appropriate, for the average weekday during peak periods and peak hours. Changes will be noted. In addition, a questionnaire survey in neighborhoods adjacent to I-66 will solicit information on the noise barriers, lighting, and general impacts of I-66.

Local Response to I-66

Information on local reaction to I-66 and on the effectiveness of the marketing and public information campaign obtained through the means previously mentioned will be reviewed, analyzed, and summarized.

Performance of TMS on I-66 and I-395

The performance of the TMS will be measured by calculating V/C ratios during peak and off-peak hours at locations along the two facilities and comparing them with acceptable ratios. Average speeds during peak and off-peak hours will be calculated and compared with acceptable speeds. Finally, selected accident statistics will be calculated for comparison with typical accident levels. In the case of I-395, the statistics cited above will be developed for the facility prior to the installation of the TMS so that a before-and-after performance evaluation can be made.

ACKNOWLEDGMENT

Thanks go to Harry Craft and his staff for editing and reproducing the manuscript of this paper. Funding for the evaluation study is being provided by FHWA. The opinions, findings, and conclusions expressed in the paper are ours and not necessarily those of the sponsoring agencies.

REFERENCES

1. J. Page and E. Deasy. I-66: A Study. School of Engineering and Applied Science, Univ. of Virginia, Charlottesville, 1981.
2. Proposed Four-Lane, Multimodal Concept: I-66--Final Supplemental Environmental/Section 4(f) Statement. Virginia Department of Highways and Transportation, Charlottesville, Aug. 1976.
3. Final Environmental Impact Statement: Dulles Access Highway Extension and Outer Parallel Roadways Between Routes 7 and I-495. Federal Aviation Administration, U.S. Department of Transportation, Nov. 1980.
4. JHK and Associates. Traffic Management Concepts: Interstate 66. Virginia Department of Highways and Transportation, Charlottesville, Feb. 1977.
5. JHK and Associates. Shirley Highway Operations Study. Virginia Department of Highways and Transportation, Charlottesville, Aug. 1976.
6. Howard, Needles, Tammen and Bergendoff; Sperry Systems Management. I-395/I-66 Traffic Manage-

ment System: Phase 1 Report--Preliminary Functional Design and Operations Plan. Virginia Department of Highways and Transportation, Charlottesville, July 1979.
7. JHK and Associates. Development of Traffic Management Strategies for the Dulles International Airport Access Highway: Final Report--Phase 1. FHWA, Jan. 1981.
8. JHK and Associates. Development of Traffic Management Strategies for the Dulles International Airport Access Highway: Final Report--Phase 2. FHWA, March 1981.

Publication of this paper sponsored by Committee on Transportation System Management.

Peak-Period One-Way Operation of an Urban Expressway

JOHN F. TEMPLE

The evaluation of an experimental urban traffic control strategy designed to reduce recurring congestion on the Arlington Expressway in Jacksonville, Florida, is described. The 60-day experimental project involved the daily conversion of a 2.8-mile section of the expressway to one-way operation toward the downtown area during the morning peak period and one-way operation out of the downtown area during the evening peak. The one-way operational plan, which provided temporary additional capacity for the peak direction, was developed by the Jacksonville Traffic Engineering Department and approved for implementation by the Florida Department of Transportation (FDOT). The effectiveness of the one-way strategy was measured by using before and after studies. The primary objectives of the evaluation were to identify existing points of congestion and quantify the delay incurred, to measure travel-time savings realized by motorists who used the one-way operation, and to compare user benefits with the negative effects experienced by motorists forced to divert to alternative routes. The results of the before study identified a four-lane bridge (Mathews Bridge) as the primary capacity constraint for peak-period traffic entering and leaving the downtown Jacksonville area. The one-way operation, in effect, doubled the capacity of this bridge to serve the peak directional flow and eliminated the recurring congestion that had developed on its approaches. During the morning westbound one-way operation, stopped delay at the Mathews Bridge toll plaza was reduced 78 percent in the peak half-hour. During the evening eastbound operation, average running speed on the expressway improved by 56 percent. Motorists entering and leaving the downtown area opposite to the peak directional flow experienced increased trip length and travel time as a result of the requirement to use alternative routes, but these increases were not unreasonable. Analysis of the systemwide impacts on fuel consumption showed a marginal net benefit. After the evaluation, FDOT approved indefinite continuation of the one-way strategy.

In July 1981, the Jacksonville Transportation Authority (JTA) and the Jacksonville Traffic Engineering Department approached the Florida Department of Transportation (FDOT) with a plan for easing morning and evening traffic congestion on the Arlington Expressway, a four-lane, limited-access facility that links downtown Jacksonville with residential areas located to the east across the St. Johns River. The plan involved daily conversion of a 2.8-mile section of the expressway to one-way operation toward downtown during the morning peak period and one-way operation out of the downtown area during the evening peak.

The FDOT acknowledged the need to improve peak-period conditions on the expressway and recognized the potential for a low-cost, high-benefit freeway management strategy that would be of widespread interest should the concept prove to be successful. Accordingly, FDOT approved an experimental demonstration period of 60 days, during which an evaluation of the one-way operation would be conducted. The Research and Studies Section of the FDOT Bureau of Traffic Operations was assigned the responsibility for developing and implementing the evaluation. This paper documents the results of that study.

The material presented here primarily addresses the impact on those traffic operational characteristics that could be satisfactorily measured through comparative studies conducted in the weeks just before and during the 60-day experimental period.

ONE-WAY OPERATION

Project Location

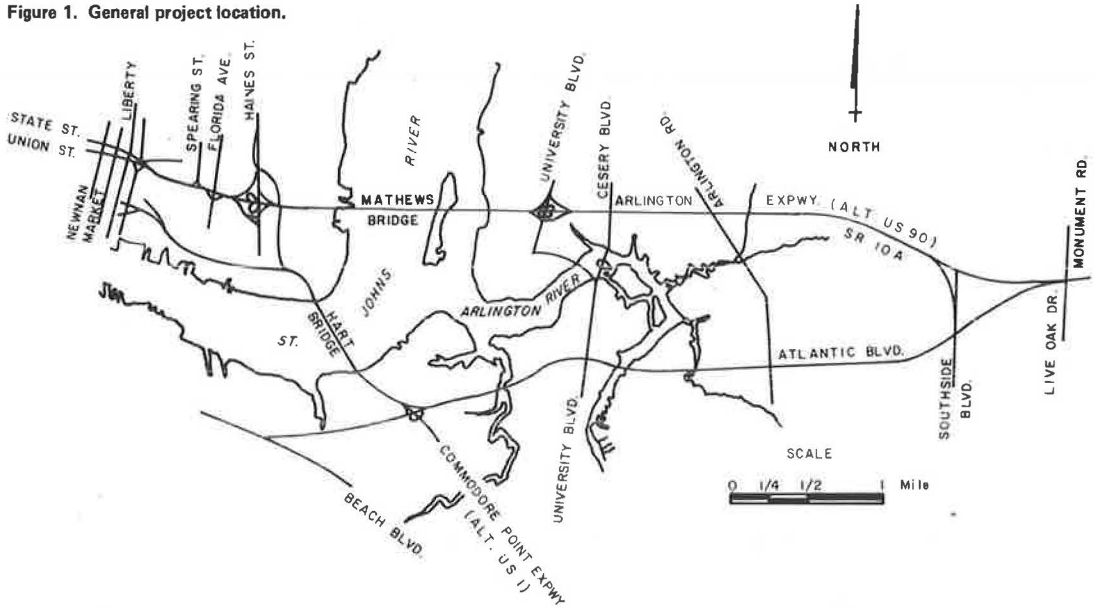
Downtown Jacksonville is located in the central portion of Duval County and is situated on the St. Johns River, which separates the downtown area from numerous suburbs to the east and southeast. A total of five bridges span the river within a distance of 4 miles (see Figure 1).

The Arlington Expressway is an easterly extension of State and Union Streets, which are prominent one-way arterials that accommodate downtown travel in the westbound and eastbound directions, respectively. The expressway is designated as Alternate US-90 and FL-10A. Full control of access on the expressway begins at Liberty Street and extends eastward over the river by way of the Mathews Bridge to Southside Boulevard, a total length of 5.7 miles. Located at the eastern terminus of the Mathews Bridge is a toll plaza at which motorists crossing the bridge in either direction must pay the required toll.

On the west side of the river between Liberty Street and the Mathews Bridge are three interchanges. Two serve low-volume surface collectors in residential areas on the fringes of the central business district (CBD), and the third provides a connection to Alternate US-1 and Haines Street. Haines Street provides access to Jacksonville's Gator Bowl and the surrounding riverfront industrial area. Alternate US-1 south of the Haines Street interchange becomes the Commodore Point Expressway and crosses the St. Johns River via the Isaiah Hart Bridge, located approximately 1 mile south of the Mathews Bridge. Like the Mathews Bridge, the Hart Bridge is a toll facility and has a similar toll schedule.

On the east side of the Mathews Bridge, there is a major interchange at University Boulevard, approximately 1100 ft east of the toll plaza. Between University Boulevard and Southside Boulevard, the Arlington Expressway is flanked by frontage roads with slip ramps that provide ingress and egress. Only two additional north-south streets, Cesery Boulevard and Arlington Road, provide connections between areas separated by the expressway on the east side of the river.

Figure 1. General project location.



Strategy

The objective of the one-way operation was to relieve the congestion on the expressway for inbound traffic (westbound) during the weekday morning peak period and for outbound traffic (eastbound) during the evening peak. Congestion developed in the morning in the vicinity of the toll plaza due to heavy approach volumes from the two expressway lanes to the east and from the University Boulevard entrance ramps, which continue as added expressway lanes from the interchange to the toll plaza. The capacity of the immediate approach to the toll plaza, therefore, exceeded the two-lane capacity of the Mathews Bridge, which is inherently constricted by limited lateral clearances and steep grades. The two westbound lanes of the expressway on the west side of the river have no difficulty in accommodating traffic flowing over the bridge, and from the west end of the bridge to Liberty Street the expressway operated without congestion.

During the evening peak a similar situation occurred, except in the eastbound direction. High approach volumes on the two eastbound lanes combined with a high entering volume on the Haines Street interchange ramps at the west end of the bridge resulted in congestion that backed up traffic on the expressway at the beginning of the bridge. During both peak periods, the Mathews Bridge was incapable of accommodating the traffic flow rate accommodated on its approaches.

To relieve this recurring congestion, authorities felt it necessary to increase the capacity of the Mathews Bridge in the peak direction. Various alternatives, including the contraflow operation of a single additional lane in the peak direction, were dismissed due to safety considerations. The preferred strategy called for a total conversion of all expressway lanes to the peak direction between Liberty Street on the west and the Mathews Bridge toll plaza on the east.

During periods of one-way operation, toll collectors in booths that normally serve traffic traveling opposite the peak direction collected tolls from motorists who were diverted across the toll plaza through these booths and onto the Mathews Bridge in the converted lanes. All entrance and exit ramps connecting to the converted side of the expressway were barricaded to prevent conflicting traffic movements. Additional traffic control and minor detouring were required downtown in the immediate vicinity of Liberty Street in order to allow one-way traffic to enter and exit the freeway. Signs, barricades, and uniformed police officers were used for this purpose. Morning and evening one-way operations are shown in Figures 2 and 3.

In consideration of unfamiliar motorists who might be following designated U.S. routes, Alternate US-90 was rerouted for the experiment to other facilities not affected by the one-way operation. Realizing that a complete conversion of even a short section of the expressway that included the Mathews Bridge would require motorists traveling opposite the peak direction to use an alternate route to cross the St. Johns River, authorities wished to limit the duration of the one-way operation as much as possible so that the desired additional peak-direction capacity would be provided only when needed and inconvenience to opposing traffic would be minimized.

Investigation of traffic data led authorities to determine that 45 min of one-way operation was required in both the morning and the evening. It was estimated that the time required to terminate opposing traffic, to set up the necessary traffic barricades on access ramps, and to clear the section of expressway to be converted would total 15 min. A similar time was allowed to reverse the process and return the expressway to normal operation at the end of each one-way period. The total time for conversion, operation, and reversion was therefore estimated to be 1.25 h. The anticipated schedules for morning and evening operation are given in Table 1.

Before initiation of the one-way experiment, Jacksonville newspapers printed a significant amount of information on how and when the expressway would be converted and what alternative routes were available.

EVALUATION PLAN

Objectives

The purpose of the Arlington Expressway experiment was to increase temporarily the capacity of the facility to accommodate peak traffic flows and thereby

Figure 2. One-way operation of Arlington Expressway: morning peak.

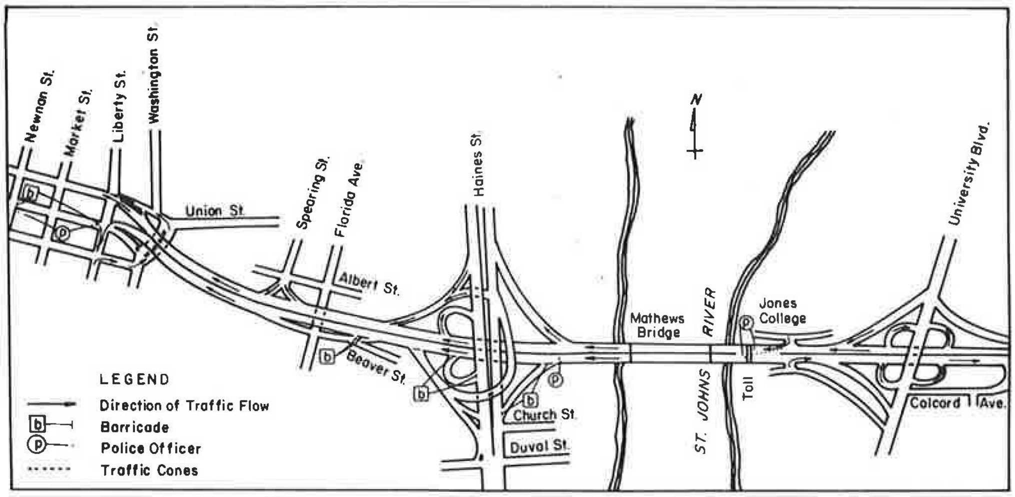


Figure 3. One-way operation of Arlington Expressway: evening peak.

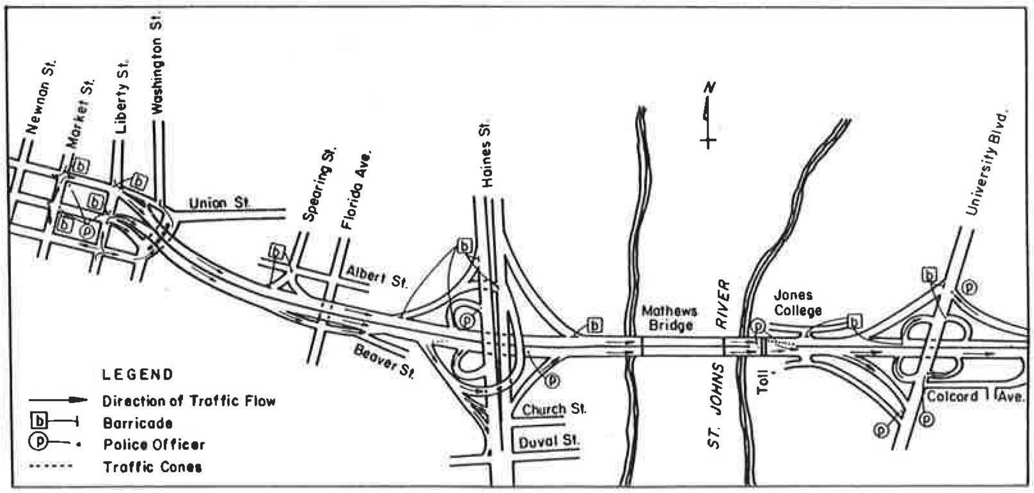


Table 1. Anticipated schedule of one-way operation.

Item	Morning Period (a.m.)	Evening Period (p.m.)
Ramp closures and expressway clearance	7:15-7:30	4:45-5:00
One-way operation	7:30-8:15	5:00-5:45
Expressway clearance and barricade removal	8:15-8:30	5:45-6:00

reduce the recurring congestion and delay experienced by motorists. To evaluate the effectiveness of the strategy, a series of before and after studies was conducted to measure the impacts on traffic flow. Three primary objectives were established for the evaluation:

1. Identify points of congestion and measure the delay incurred,
2. Measure the travel-time savings realized as a result of the one-way operation, and
3. Compare the benefits derived by motorists using one-way operation with the negative effects incurred by motorists forced to divert to alternative routes.

Data Collection Techniques

Study of Toll Plaza Operations

Because congestion developed during the morning peak period in the area of the toll plaza at the east end of the Mathews Bridge, there was some speculation that the toll booths were the constraining factor and that additional toll collectors would help alleviate the long queues on the approach to the plaza. Other concerned parties suggested that the Mathews Bridge, with only two westbound lanes, was the ultimate capacity constraint. To study the problem, time-lapse photography from a 12-story building near the toll plaza was used.

Films were taken continuously from 6:30 to 8:00 a.m. on two weekdays before initiation of the experimental one-way operation. Similar films were taken on the same weekdays two weeks after the one-way operation had been in effect. From these films (8 mm at 2 frames/s), changes in lane volume distribution, toll booth processing rate, and delay in queues waiting to pay tolls were determined.

Speed and Delay Studies

To measure travel-time savings experienced by motorists using the Arlington Expressway, moving-vehicle speed and delay studies were conducted. Terminal nodes for the study section were established in downtown Jacksonville on the west and at Monument Road on the east. The resulting route length was 6.6 miles. These locations were selected because they represented logical diversion points for traffic forced to travel an alternative route during the periods of one-way operation.

Figure 4. Traffic volume on Mathews Bridge over 24-h period.

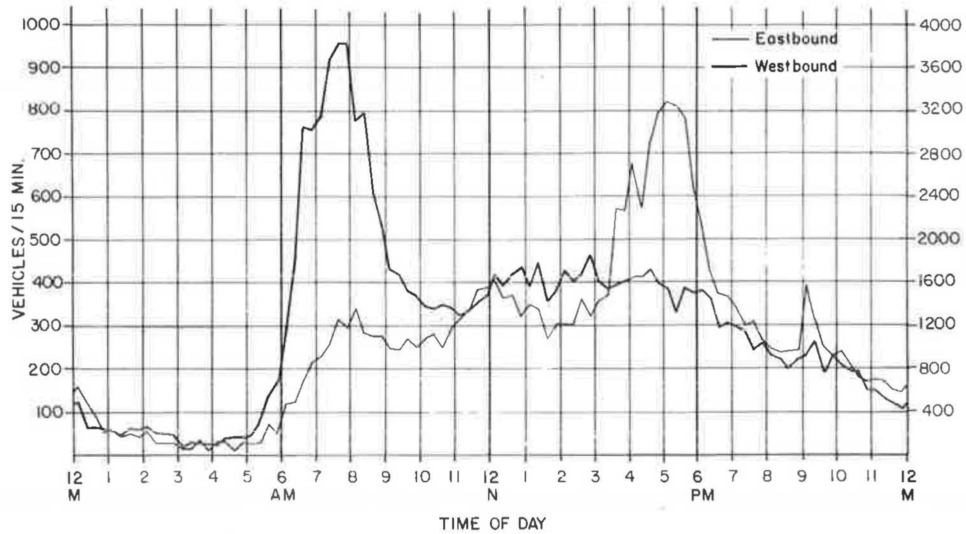


Table 2. Directional traffic flow during periods of one-way operation.

Peak Period	Eastbound Volume	Eastbound Percent	Westbound Volume	Westbound Percent	Total Volume
7:15-8:15 a.m.	1215	25	3605	75	4820
4:45-5:45 p.m.	3207	76	1017	24	4224

Intermediate nodes were established at all interchanges and signalized intersections on the Arlington Expressway route and on the Atlantic Boulevard-Hart Bridge route, which was the most direct diversion corridor. Speed and delay studies were made on the diversion route as well to determine any negative impacts on those facilities and to quantify the increased travel time incurred by diverted motorists.

Study of Expressway Volume Throughput

To monitor the effectiveness of the one-way operation in allowing greater volumes of traffic to move to and from the downtown area during peak periods, traffic counts were made at all ingress and egress points on the Arlington Expressway from Liberty Street to University Boulevard. Observers with synchronized watches were stationed at various vantage points along the corridor, and they monitored entering and exiting traffic volumes traveling in the peak direction. Volumes were recorded at the end of each 3-min interval.

Traffic Counts Along Alternative Route

To estimate the volume of traffic that was forced to travel the alternative route to and from Jacksonville opposite the peak direction, 15-min traffic counts were taken during the periods of one-way operation at major intersections along Atlantic Boulevard. These counts were taken on individual days before and after the one-way operation began. They were used, along with toll collection data at the Hart Bridge, to estimate not only the volume of traffic that was diverted but also where along the route this volume entered or departed. By analyzing these volumes and speed and delay data, estimates could be made of the total additional travel time and delay experienced by diverted motorists.

EXISTING OPERATIONAL CHARACTERISTICS

Traffic volume counts obtained on the Mathews Bridge portion of the Arlington Expressway showed a daily use of approximately 55 000 vehicles. Flow profiles for eastbound and westbound directions are shown in Figure 4, and from this figure the distinct morning and evening peak directional flows can be seen.

With the one-way operation in effect, motorists traveling opposite the peak direction would be forced to adjust their departure time or to use an alternative route. Directional traffic flow during morning and evening peak periods of one-way operation is given in Table 2. During both peaks, the potential exists for diversion of about 25 percent of the total traffic crossing the St. Johns River.

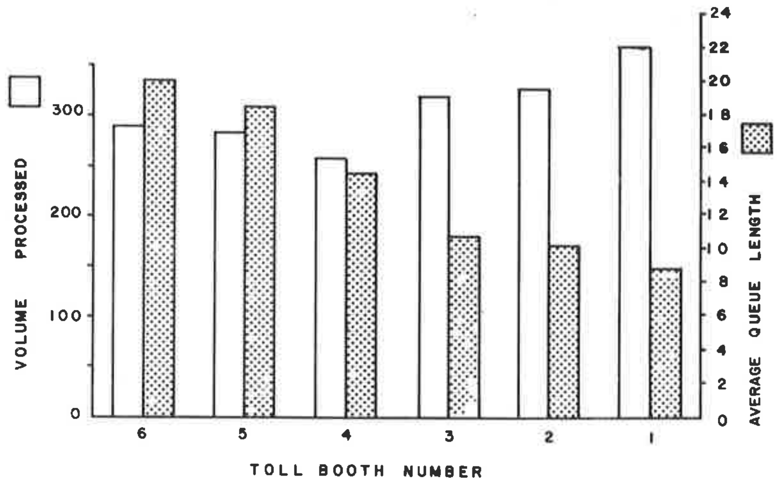
Morning Peak Period

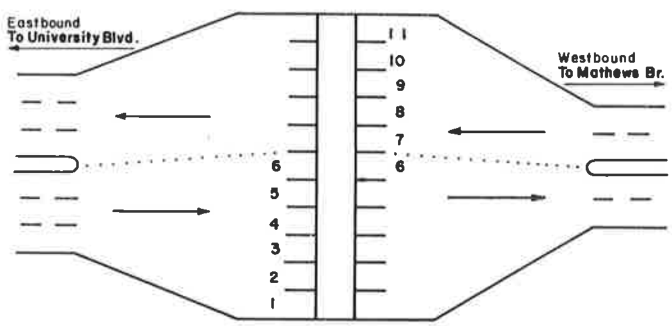
During the morning peak, 6 of the 11 tollbooths at the Mathews Bridge toll plaza serve the eastbound traffic (booths 1-6). Figure 5 shows for each of these booths the volume of traffic served between 7:30 and 8:00 a.m. and the average number of vehicles in the queue waiting to pay the toll. The histograms reveal that, whereas use of the booths is approximately uniform, the queue for each is not.

Motorists approaching the plaza from the expressway to the east were reluctant to use tollbooths 1-3 unless the queues there were very short. This is due to the fact that they would then have to merge back into the main traffic stream processed by booths 4-6. As the queues for booths 4-6 became longer and began approaching University Boulevard, westbound traffic entering the expressway at that interchange had no choice other than booths 1-3 because queues at other booths extended beyond their entry point. As a result, all available tollbooths were continuously used during the peak half-hour. Therefore, although approaching traffic could be redistributed to result in more uniform queue lengths, the total vehicle delay would remain unaffected.

Analysis of film footage of the toll plaza operation revealed that, on the average, each tollbooth processes a vehicle every 6.0 s. With six booths operating, this produces a throughput rate of 3600 vehicles/h. The Mathews Bridge, with its limited lateral clearances and steep grade, is marginally capable of accommodating this volume. The area between the toll plaza and the bridge became intermittently jammed during the peak, such as when the

Figure 5. Tollbooth use before one-way operation use: 7:30-8:00 a.m., westbound.





momentary throughput rate at the plaza exceeded the average or when a truck or bus labored up the bridge incline. Therefore, providing additional tollbooths to serve peak morning traffic without increasing the capacity of the Mathews Bridge would only cause greater congestion on the approach to the bridge and further restrict flow.

Vehicle delay at the toll plaza was quantified through analysis of the time-lapse films. Several hundred randomly selected vehicles were tracked through the toll plaza, and their time in a queue was recorded. The upper portion of Figure 6 shows average stopping delay in a queue during the morning peak half-hour (7:30-8:00 a.m.) and the lower portion shows 3-min approach volumes arriving between 7:00 and 8:30 a.m. In comparing the two graphs, it can be seen that delay in a queue continues to increase as long as the 3-min approach volume steadily exceeds 180 vehicles, which equals the mean processing rate of the six tollbooths combined (6.0 s/vehicle/booth). At about 7:52 a.m., when the approach volume drops below the 200 mark, delay begins to decrease dramatically as the six tollbooths can process more vehicles than are approaching. During the peak half-hour, the average stopped delay for all six booths was 91 s. Individual delays were measured as high as 3 min, 27 s.

Once a motorist had passed the toll plaza and entered the bridge, flow over the bridge and into the downtown area was uninterrupted unless there was an incident on the bridge.

Evening Peak Period

Evening traffic crossing the Mathews Bridge in the eastbound direction enters the expressway at two major points. Approximately 50 percent enters from Union Street, and about 40 percent enters at the Haines Street interchange. Figure 7 shows a comparison of input volume at these major ingress points during the evening peak.

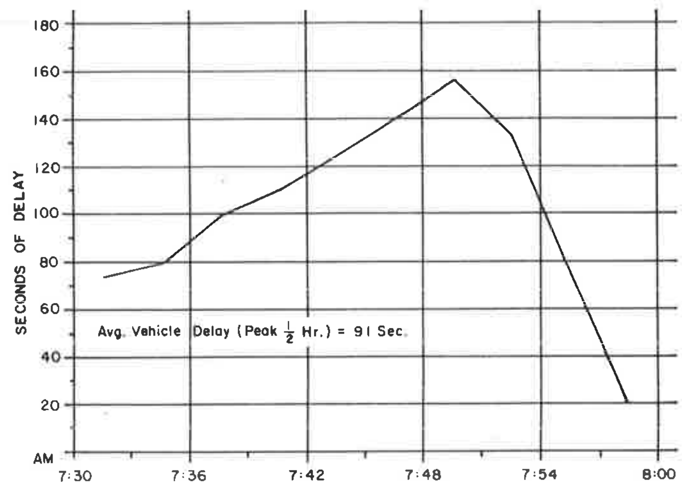
Entrance to the expressway from Union Street is controlled by a traffic signal at Liberty Street. Entrance at the Haines Street interchange is accomplished on one of two free-flow ramps, one from northbound Haines Street and one from southbound Haines Street. As the flow rate on the expressway approaches the capacity of the bridge (at approximately 4:35 p.m.), congestion develops at the west end of the bridge and extends westward through the Haines Street interchange area. The bumper-to-bumper flow along the expressway makes merging maneuvers at the two Haines Street ramps very difficult. As a result, motorists entering at this interchange experience delays as long as 6 min around 5:00 p.m. Once a vehicle is on the bridge, speed increases again and travel is uninterrupted except for stops at the toll plaza.

Travel-time data for speed and delay runs made in the eastbound direction are shown in Figure 8. The average of eastbound runs made with the peak flow between 4:00 and 6:00 p.m. (nine runs) is plotted against the average of eastbound runs made between 7:00 and 8:30 a.m. (eight runs), which represents an off-peak period for this direction. Figure 8 reveals that virtually all of the excess travel time experienced with the peak flow in the evening occurs between Liberty Street and the beginning of the bridge. Average running speed in the evening was only 22 mph between these points; in the morning it was 45 mph. The remainder of the trip shows no appreciable difference, including the delay at the toll plaza. The similarity in toll plaza delay for eastbound morning and evening traffic is due to the previously discussed relation between the capacity of the Mathews Bridge and the mean processing rate of the tollbooths. As in the morning period, 6 of the 11 tollbooths are servicing the major traffic flow in the evening.

RESULTS OF ONE-WAY OPERATION

The peak-period one-way operation of the Arlington Expressway began as scheduled on the morning of Tuesday, August 18, 1981. Reversal of the eastbound lanes to the westbound direction commenced with the radio-coordinated unveiling of temporary guide signs and placement of barricades at all eastbound entrance ramps in the downtown area. After a brief period, a police officer on a motorcycle would drive from Liberty Street to the toll plaza to ensure that the last vehicles allowed on the eastbound lanes had successfully cleared the section of the expressway

Figure 6. Average stopped delay at toll plaza before one way-operation: 7:30-8:00 a.m.



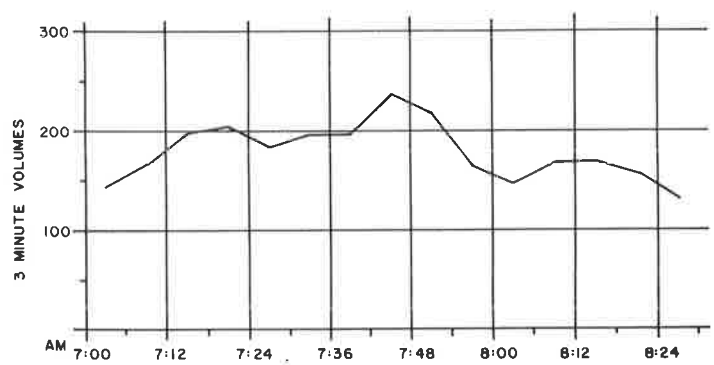


Figure 7. Arlington Expressway input volumes before one-way operation: eastbound, evening.

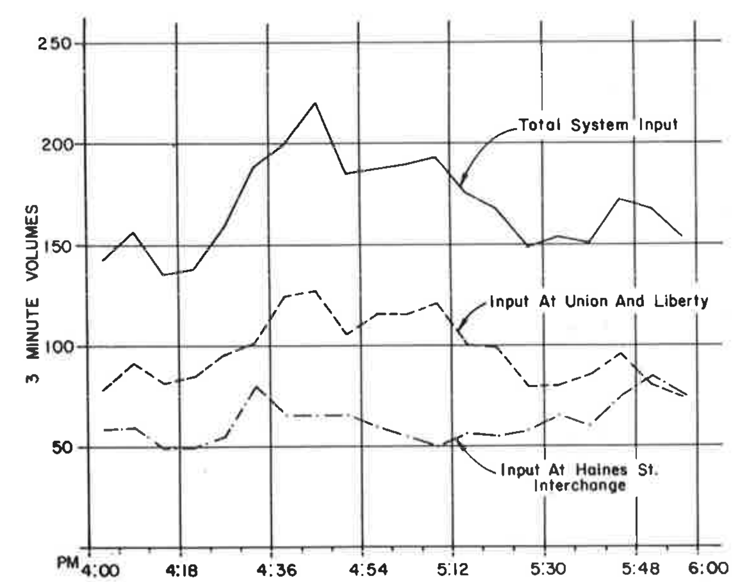
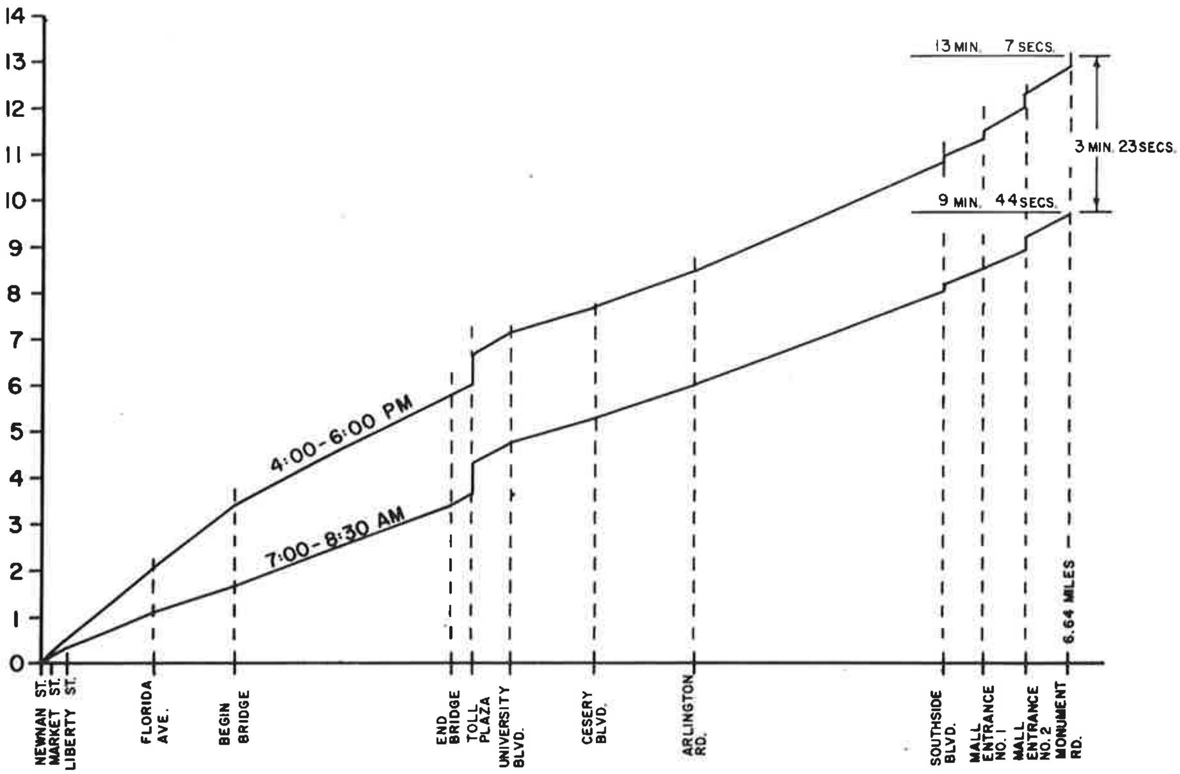


Figure 8. Travel time and delay before one-way operation: eastbound, evening versus morning.



to be reversed. Once this was accomplished, westbound traffic approaching the toll plaza in the median lane of the expressway was channelized with traffic cones through tollbooths 6-9 and onto the Mathews Bridge. Because of the median barrier that extends from the eastern end of the bridge to downtown, traffic in the contraflow lanes was unable to exit before reaching Union Street at Liberty Street. Here, contraflow traffic was forced to turn north or south onto Liberty since Union Street remained one-way eastbound beyond that point.

Conversion of the expressway to one-way operation in the evening was accomplished in a similar manner, and temporary guide signs and barricades were used as rapidly as possible. After a police officer drove the facility westbound and verified clearance, other uniformed officers downtown diverted traffic from Union Street one block north to State Street and eastward onto the contraflow lanes. This traffic was also required to travel the 2.8 miles to the toll plaza without exiting. At the plaza, booths 3-11 served eastbound traffic, which was channelized back to the normal lanes just beyond the plaza.

Promotional literature and press releases issued by Jacksonville authorities had stated that one-way operations would be in effect from 7:30 to 8:15 a.m. and from 5:00 to 5:45 p.m., with 15-min transition periods before and after each reversal. Under normal, incident-free conditions, authorities were able to routinely accomplish the transitions in about 5 or 6 min, which resulted in actual one-way periods from 7:20 to 8:20 a.m. and from 4:50 to 5:50 p.m.

Effect of Morning One-Way Operation

Allowing the eastbound lanes of the Arlington Expressway to operate in the westbound direction in effect doubles the capacity of this facility to carry vehicles from Arlington to downtown Jacksonville. With nine booths open to approaching traffic instead of six, the change in the length of queues was quite dramatic. Figure 9 shows histograms of tollbooth use and average queue length for the peak half-hour when one-way operation was in effect. In comparing Figure 9 with Figure 5, it can be seen that the average queue lengths before ranged from 9 to 20 vehicles and the maximum average queue length after was fewer than 3 vehicles.

As Figure 10 shows, shorter queues at the toll plaza mean less delay. Superimposed on the delay curve for the "before" condition is the average vehicle delay during the peak half-hour of one-way operation. The average stopped delay at the toll plaza was reduced from 91 to 20 s, a reduction of 78 percent. The volume of approaching traffic for which these delays were measured was actually greater during one-way operation, as shown in the lower portion of Figure 10.

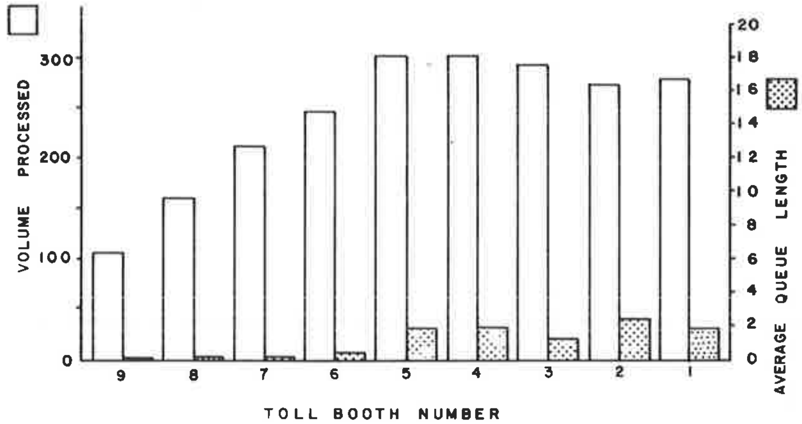
During the one-way operation from 7:20 to 8:20 a.m., an average of 4273 westbound vehicles crossed the Mathews Bridge. Of these, 31 percent traveled in the contraflow lanes and 69 percent in the normal manner.

Travel time and delay data for moving-vehicle studies made between 7:20 and 8:20 a.m. both before and after initiation of the one-way operation are shown in Figure 11. Only data for the portion of the route between University Boulevard and Liberty Street are depicted because travel time on expressway segments east and west of these points was unaffected. A total of five runs in the "before" condition were compared with four runs in the "after" condition. As expected, the only appreciable difference brought about by the one-way operation is a reduction in delay at the toll plaza.

Effect of Evening One-Way Operation

Analysis of the eastbound evening flow in the "before" condition revealed that the majority of the

Figure 9. Tollbooth use after one-way operation: 7:30-8:00 a.m., westbound.



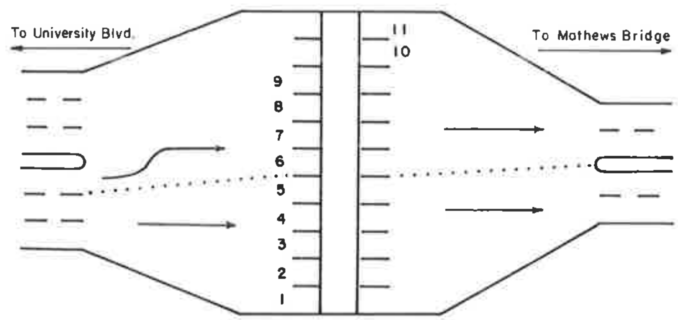
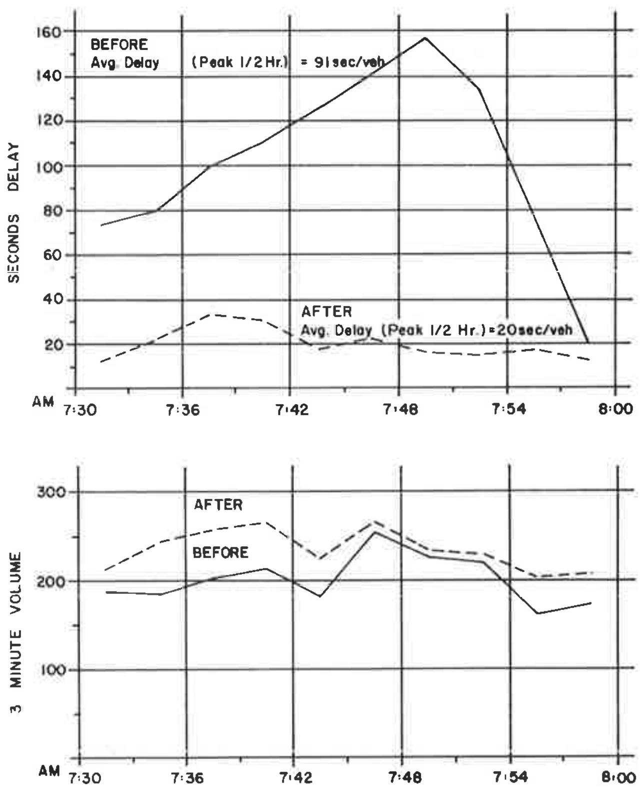


Figure 10. Approach volumes and stopped delay at toll plaza during one-way operation: 7:30-8:00 a.m.



delay occurred between Liberty Street and the beginning of the bridge and also on the Haines Street ramps for those vehicles that attempt to enter the expressway at that interchange. With the one-way operation in effect, all of the traffic approaching the expressway on Union Street was diverted to State Street and forced to cross the bridge on the contraflow side. This is a significant percentage of the total traffic using the Mathews Bridge during this period. In contrast to the morning period, when 31 percent of the vehicles traveled in the contraflow lanes, during the evening one-way operation 42 percent of the 3683 vehicles using the bridge traveled in the contraflow lanes. As a result, traffic passing the Haines Street interchange entrance ramps was greatly reduced, and motorists entering the expressway at this location experienced no delay.

As Figure 12 shows, the elimination of delay on the southbound Haines Street ramp had a profound effect on the traffic using this expressway entrance. Between 4:50 and 5:50 p.m., ramp volume averaged 544 vehicles in the "before" study. During this period in the "after" study, volume increased to 892 vehicles. Although verification studies were not made, it is believed by those familiar with the experiment that the increased traffic using this ramp during the period of one-way operation was traffic that, on perceiving the congestion that prevailed before the experiment, had opted to continue southbound on Haines Street, crossing the St. Johns via the Hart Bridge, which was operating quite freely.

Effects of the one-way operation on travel time eastbound in the evening are shown in Figure 13. A total of four runs made during the "before" condi-

Figure 11. Travel time and delay: before and after one-way operation, westbound, 7:20-8:20 a.m.

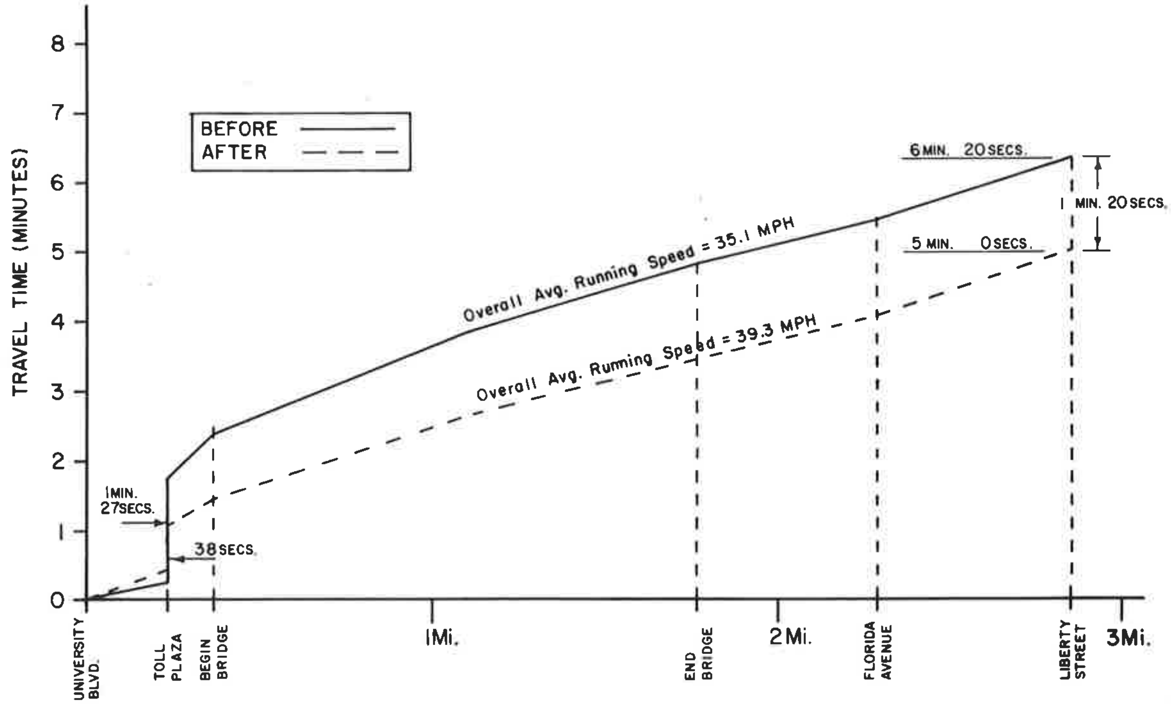
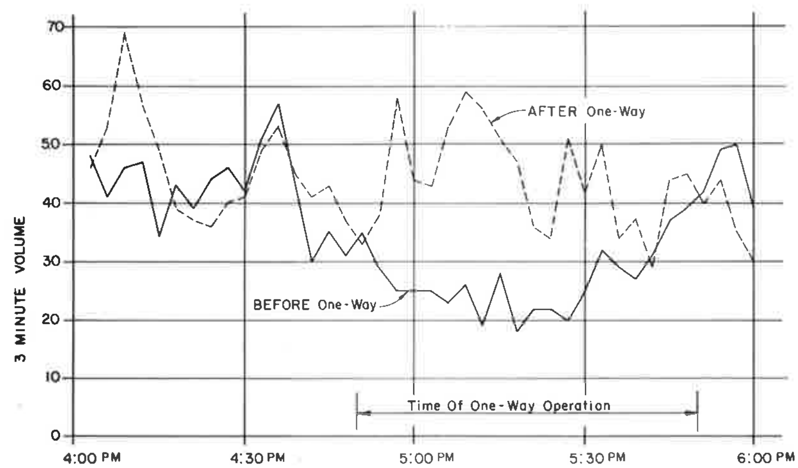


Figure 12. Input volume from southbound Haines Street to eastbound Arlington Expressway.



tion were compared with six runs made during the one-way operation. The average travel time for runs made between 4:50 and 5:50 p.m. was 3 min and 5 s shorter during the one-way operation. As expected, the most significant reductions occurred between Liberty Street and the beginning of the Mathews Bridge. Average running speed, which in this case is the travel distance divided by total travel time minus stopped delay at the toll plaza, increased from 23 to 35 mph.

It must be noted that, because a true evaluation of the improvements in travel time and delay resulting from the one-way operation required a comparison of only those "before" and "after" runs conducted during the very brief time frames of 7:20-8:20 a.m. and 4:50-5:50 p.m., the limited number of such runs did not provide statistically significant differences in average travel times. However, continued observation of the one-way operations led the evaluation team to conclude that the differences indicated by the analysis are an accurate measure of the improvements derived under incident-free conditions.

Figure 14 shows a histogram of tollbooth use for the evening peak half-hour. Because of the traffic cone configuration used at the toll plaza, booths 4 and 5 service higher volumes than the seven others. Later in the experiment, after city traffic engineering staff and toll plaza management had perceived a continual underuse of booth 6, traffic cones were realigned to channelize contraflow traffic through that booth. This made tollbooth use more uniform.

Net Effect on Fuel Consumption

To estimate the systemwide net effect on fuel consumed by motorists crossing the St. Johns River, the estimated fuel savings of motorists who benefited from the one-way operation were compared with the excess consumption experienced by diverted motorists forced to use the alternative routes. Average travel times, stopped delays, and speeds served as inputs to fuel consumption equations (1). Traffic volume data, collected along the Arlington Expressway and Atlantic Boulevard-Hart Bridge corridors, were analyzed to establish the volume of diverted motorists and the points from which they diverted. For Arlington Expressway users, savings were derived from comparison of "before" and "after" data collected on the expressway within the one-way operational time periods. For diverted motorists, excess fuel consumption was derived from a comparison of travel time data obtained from runs made on the Arlington Expressway before implementation and runs made on the diversion route after one-way operation began.

As demonstrated earlier, total travel time on the Arlington Expressway in the morning was essentially unchanged by the one-way operation except for the reduction in stopped delay at the toll plaza. The

Figure 13. Travel time and delay: before and after one-way operation, eastbound, 4:50-5:50 p.m.

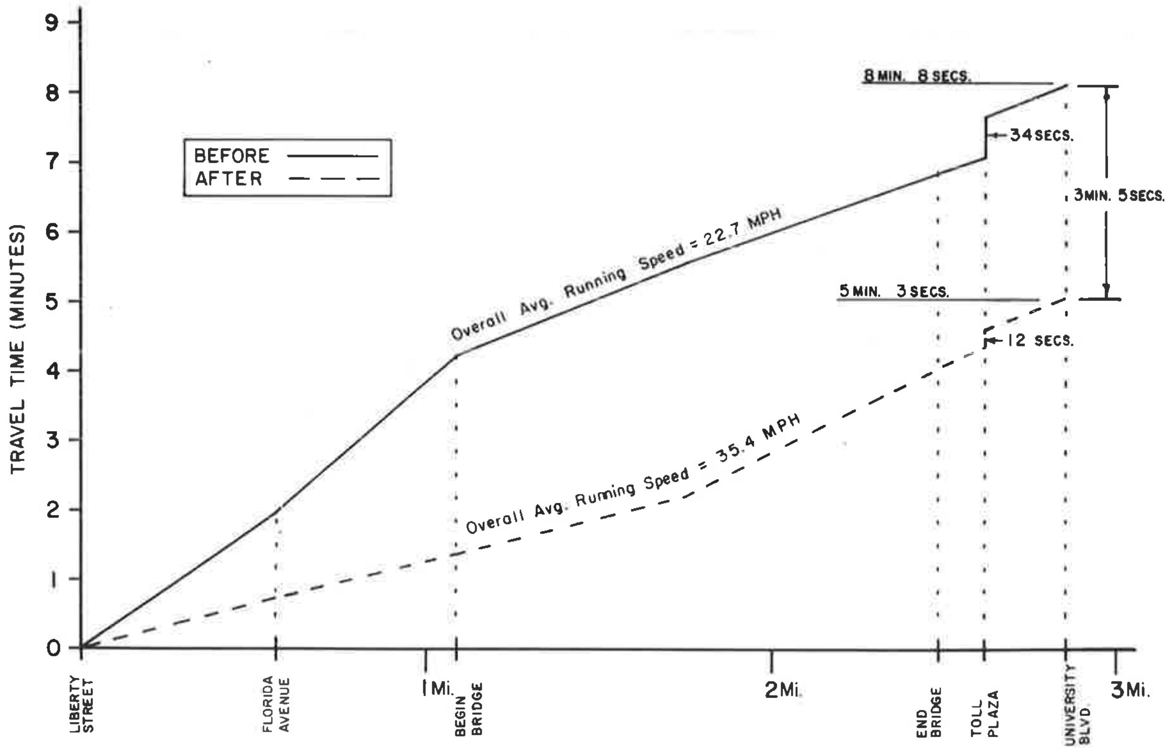
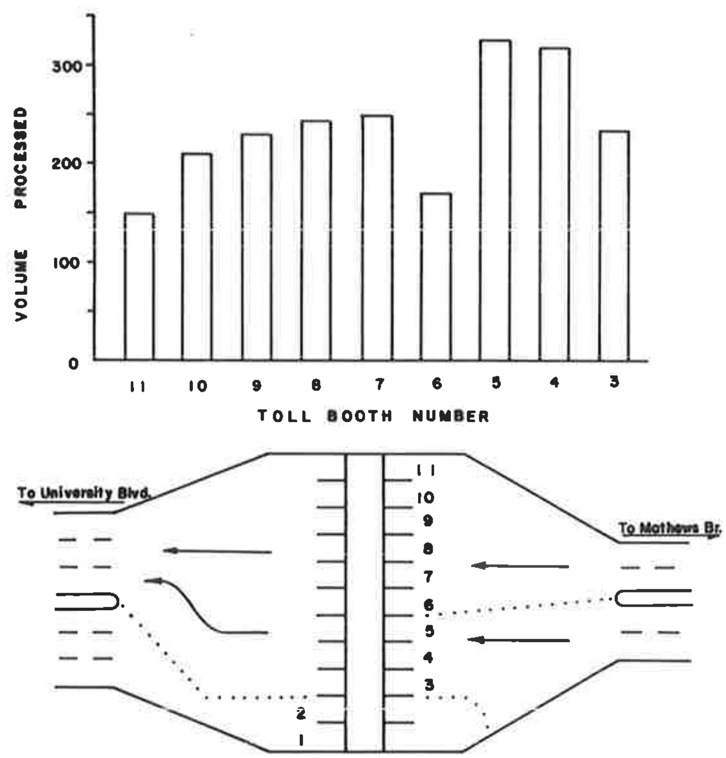


Figure 14. Tollbooth use during one-way operation: 4:30-5:00 p.m.



fuel savings brought about by this reduction in delay westbound were not sufficient to offset the excess fuel consumed by the volume of eastbound traffic that followed the identified diversion routes from downtown to areas east of the river. When calculated per-vehicle fuel consumption values for the various routes were multiplied by the measured volumes of traffic using those routes, it was estimated that the net effect was a 13-gal increase in fuel consumed during a single morning period.

During an evening period, when expressway motorists experienced greater reductions in delay and also improvements in average speed, the analysis of fuel consumption indicated a net savings of 25 gal. The estimated overall net effect from a single day's operation of the one-way strategy was therefore a savings of some 12 gal of fuel.

It is important to note that the above figures do not consider the significant reduction in delay realized by evening motorists entering the Arlington Expressway at the Haines Street interchange. No data were available to estimate their savings. In addition, the volume of traffic that had originally traveled the Arlington Expressway opposite the peak directions could not be totally accounted for from intersection counts made during the experiment. It is suspected that many drivers in this category altered their departure times to arrive immediately before or after the one-way periods so as to cross the river without diverting.

The fuel consumption analysis was not intended to accurately quantify the actual net effects of the one-way strategy. It served, rather, as a general indicator of the degree to which the strategy was influencing systemwide fuel consumption. From the analysis, the evaluation team concluded that overall fuel consumption was not grossly affected either positively or negatively.

CONCLUSIONS

The conclusions expressed in this section are based on the comparative analyses and on observations made by the evaluation team. Time constraints did not allow a comprehensive evaluation of such scope that all operational impacts could be analyzed, quantified, and compared to determine the absolute net effects of the one-way operation. Much of the impetus for initiating the one-way operation developed in response to those occasions when an incident on the Mathews Bridge resulted in lengthy delays and severe driver frustration. It was not intended, within the scope of this evaluation, to prepare for and monitor operations under these conditions, although they occur frequently. Certainly, because of the added capacity provided for the peak direction, the congestive effects of incidents would be greatly reduced under the one-way operational strategy.

Toll Plaza Operations

Analysis of the 8-mm time-lapse films revealed that before the experiment the toll plaza operation was conducted quite efficiently and that, particularly in the morning, the optimal number of tollbooths were open to serve peak directional flows. This finding is contrary to opinions expressed by some that additional available tollbooths would, in and of themselves, reduce queue lengths and stopped delay. Without the one-way operation, additional booths to serve the inbound morning traffic would have resulted in greater congestion between the toll plaza and the bridge. However, with the one-way operation in effect, additional available tollbooths for the peak direction were of significant benefit.

Morning One-Way Operation

Delays experienced by westbound morning traffic occurred between University Boulevard and the beginning of the Mathews Bridge. The one-way operation was effective in reducing this delay by 78 percent during the peak half-hour. Motorists who opted to use the converted lanes of the expressway could do so with ease. As a consequence, they were prevented from exiting the expressway before its termination downtown. This restriction posed no problem, however, because the vast majority of the traffic is commuter traffic and drivers soon familiarized themselves with the operation and the options available. Aside from the reduction in delay on the approach to the Mathews Bridge, no additional improvements in travel time could be identified.

Evening One-Way Operation

Greater benefits were derived from the one-way operation during the evening peak period. Average running speed increased from 23 to 35 mph between Liberty Street and University Boulevard. Congestion on the expressway in the vicinity of the Haines Street interchange was virtually eliminated, and vehicles entering the expressway here were unimpeded in doing so.

Impact on Diverted Motorists

Preliminary traffic counts showed a potential for diversion of 25 percent of the total traffic crossing the Mathews Bridge during the scheduled periods of one-way operation. This volume of traffic could not be totally accounted for in the analysis of the Atlantic Boulevard-Hart Bridge alternative route. It is unlikely, though, that any appreciable diversion to other alternative routes took place. Therefore, it is concluded that the majority of motorists have modified their departure times in response to the expressway closure schedule. This is substantiated by data that show increased approach volumes at the toll plaza immediately before and after conversion of the expressway.

Those motorists who did divert from the Arlington Expressway to the Atlantic Boulevard-Hart Bridge route at the common termini of the two study corridors did not experience unreasonable increases in travel time and delay to and from downtown Jacksonville, nor did the additional volumes on the alternative route result in any noticeable changes in congestion in that corridor.

Attainment of Objectives

When the effects of both the morning and evening operations are combined, the excess fuel consumed is approximately equal to that saved. No monetary value was assigned to either the fuel measures or the travel time and delay measures. These values would be speculative, and a comparison would be incomplete without consideration of implementation costs and long-term impacts on toll revenues.

The objective of the one-way operation implemented in this experiment was to eliminate the recurring congestion and resulting delay experienced by peak commuter traffic entering and leaving downtown Jacksonville via the Arlington Expressway. It was understood that some inconvenience and additional expense would be realized by those motorists who were required to use alternative routes. In view of the data presented in this paper, it must be concluded that the stated objective was accomplished by the one-way strategy.

The Jacksonville Police and Traffic Engineering Departments have demonstrated their ability to routinely implement the one-way operation well within the publicized time limits for conversion. Other than the diversion necessitated by the one-way operation, no additional adverse effects were identified either on the expressway or on the surface streets that provide access.

Perhaps the most significant aspect of the one-way operation is the newfound ability to maintain peak traffic flow across the St. Johns River during an incident on the Mathews Bridge. Previously, a stalled vehicle or accident on the bridge would have brought traffic to a standstill until the involved vehicles could be removed. The flexibility of the one-way plan, particularly in the morning, allows assignment of a large percentage of the traffic to either side of the barrier wall in response to an incident. This maintains traffic flow and allows authorities to reach and clear the incident more easily, thereby reducing its overall congestive effects.

Viewing the peak-period one-way operation in the broader sense of urban freeway management, it is significant to note the degree of cooperation and commitment exhibited by the various agencies involved. The city of Jacksonville must be recognized for developing a systematic strategy directed at reducing the recurring congestion experienced by a sizeable portion of its population. The plan could only be implemented successfully with the concerted efforts of the Jacksonville Police Department, which provided on-the-street traffic control, and the Toll Facilities Office of FDOT, which altered toll collection methods to accommodate contraflow traffic.

Following a review of the evaluation by state and local authorities, FDOT approved indefinite continuation of the one-way strategy. Accordingly, city officials appropriated the necessary funds for law enforcement personnel through FY 1982/83.

ACKNOWLEDGMENT

I wish to express my gratitude to R. Henry Mock of the city of Jacksonville, who was instrumental in developing the one-way operational strategy, and to FDOT District II Traffic Operations personnel who participated in data collection activities. A special expression of gratitude is extended to Anton Huber, formerly of the FDOT Bureau of Traffic Operations, who coauthored the original evaluation report from which this paper was developed.

REFERENCE

1. Procedures for Estimating Highway User Costs, Fuel Consumption, and Air Pollution. FHWA, May 1980.

Publication of this paper sponsored by Committee on Freeway Operations.

Abridgment

Diary of a Traffic Management Team: The Houston Experience

STEVEN Z. LEVINE AND RICHARD J. KABAT

The traffic management team approach to solving transportation operational problems in a rapidly growing urban area—Houston, Texas—is discussed. The Houston Traffic Management Team, as it is referred to, is an interagency group that is composed of representatives from Harris County law enforcement agencies; city, state, and county transportation departments; and the Metropolitan Transit Authority. The team meets monthly to discuss such topics as the review of traffic control strategies for major urban rehabilitation projects, review and approval of proposed operational changes to existing facilities, and operational problems encountered by law enforcement officials. The most important result of the team's activities since its inaugural meeting in January 1981 is the communication links that have been established between all transportation-related agencies in Harris County. It is recommended that the traffic management team approach be applied when the successful operation of existing transportation facilities crosses jurisdictional boundaries, as in Harris County.

Urban traffic management solutions to freeway and city-street operational problems encountered in large metropolitan areas require the cooperation of all transportation-related agencies. Toward this goal, the District Office of the Texas State Department of Highways and Public Transportation (TSDHPT) in San Antonio formed the first corridor management team in October 1975 (1). Representatives from the San Antonio Department of Traffic and Transportation, the District Office of TSDHPT, the San Antonio Transit System, and the San Antonio Police Department were present at the inaugural meeting. It is important to note that no specific operational funds were allocated for team activities. The cost of the operational improvements discussed are borne by the member agencies as part of their normal responsibilities. Finally, the personnel involved in these meetings were people in authority at an operational level, not administrative heads who made major policy decisions. In subsequent meetings, items such as the following were discussed: traffic handling during special events, the effects of inclement weather conditions on arterial and freeway systems, high-accident-rate locations, traffic control plans, and coordination of research efforts. The success of these meetings led to the creation of traffic management teams in other Texas cities, including Beaumont, Corpus Christi, El Paso, Fort Worth, Houston, Lubbock, Midland-Odessa, and Wichita Falls.

Houston, Texas, is the principal city in Harris County. However, high population concentrations exist in other areas that are not within the Houston city limits. These areas are either self-governing municipalities, such as Baytown, Bellaire, and Pasadena, or areas that are within one of the four county precincts. Consequently, several municipal agencies are responsible for such public services as roadway maintenance, law enforcement, and traffic signal operations. For example, frontage road signal operations inside the Houston city limits are the responsibility of the City of Houston rather than that of TSDHPT.

In summary, the above characteristics demonstrate how the experience in Houston represents a unique application of the traffic management team approach. The objective of this paper is to illustrate the function of such an "interagency team" in Houston, Texas, which is a rapidly growing major urban area where the operation of existing transportation facilities crosses jurisdictional boundaries. The agencies (and personnel) involved, the topics discussed, and some results of the team's meetings are presented. It is hoped that this paper will show examples of the benefits that could be derived by other major cities that might pursue the traffic management team approach.

PARTICIPATING AGENCIES

Participating agencies in the Houston Traffic Management Team are divided into permanent team members and "ex officio" members. The permanent team members are the Metropolitan Transit Authority (for Harris County), the Houston Department of Traffic and Transportation, the Houston Police Department, the Houston Fire Department, District and Houston urban offices of TSDHPT (the organizing agency), the Texas State Department of Public Safety, and the Harris County Sheriff's and Engineer's Offices. Representatives of these agencies regularly attend the monthly meetings.

Other agencies, such as the Houston Chamber of Commerce, railroad companies, the Texas Transportation Institute, and the Federal Highway Administration, have participated on an as-needed basis. These agencies will have greater roles as the team addresses the major incident response issue.

GENERAL TEAM GUIDELINES

At the inaugural meeting in January 1981, certain guidelines for the Traffic Management Team were established:

1. Although the team itself will not have any operational authority, it is necessary that each member should be able to make reasonable commitments within his or her normal authority based on team recommendations.
2. The team will meet every month; however, meetings could take place on an as-needed basis if special or emergency situations should arise.
3. The team should maintain a low profile.
4. The endeavors undertaken by the team members should not interfere with their present workload or make it excessively burdensome.
5. The team meetings should not concentrate on only one area.
6. Team meetings should be informal and allow for frequent attendance by additional representatives from the member organizations or other related agencies.
7. The District and Houston urban offices of TSDHPT will house the meetings since their offices are centrally located.
8. Press releases of the committee's activities (if needed) will be handled by the team chairman.
9. An agenda of the topics to be discussed will be prepared and distributed prior to each meeting.
10. A secretary will handle agenda preparation, schedule meetings, and prepare monthly reports on team activities.
11. A chairman will be elected by the team to run the monthly meetings.

TEAM FUNCTIONS

The following discussion focuses on some of the team activities. These activities are excerpts from the agendas and monthly reports of meetings of the Houston Traffic Management Team.

Traffic Control Strategies

The District and Houston urban offices of TSDHPT have presented the traffic control strategies to be used on major urban freeway rehabilitation projects. Detour routes have been discussed, and some signal modifications on the parallel routes have been made by the City of Houston. On one project, the team reviewed the traffic control plan for a major resurfacing and safety project on an Interstate highway in Houston that carries an average daily traffic of nearly 200 000 vehicles. The original plans called for each of three heavily traveled cross streets to be closed for 3 months during different phases of the project. However, a subcommittee of the Traffic Management Team identified an alternative that required closing only one cross street. In addition, signal modifications necessary on the parallel frontage roads would be made by the Houston Department of Traffic and Transportation.

Review and Approval of Proposed Operational Changes to Existing Facilities

Several of the agencies have presented plans for certain transportation system management improvements (use of narrow lanes, contraflow lanes, etc.). The team considered a proposal to restripe an extremely congested major thoroughfare from three 12-ft lanes in each direction to four 9-ft lanes in each direction. This arterial carries almost 80 000 vehicles/day. The team reviewed a videotape of traffic flow on this arterial during peak periods. The camera footage was taken by one of the member agencies. After reviewing this footage and considering the relatively insignificant level of bus and truck activity on this road, the team agreed that the proposal, though radical, was appropriate. The involved agencies then took the steps necessary to accomplish the restriping. The team continues to receive reports of the success of the restriping through law enforcement and traffic engineering team members. In addition, the team favorably reviewed some time-lapse photographic footage taken on this roadway (by another member agency) after the narrow lane operation was implemented. It was noted that bus and truck traffic was not adversely affecting traffic operations.

Discussion of Operational Problems Encountered by Law Enforcement Officials

Operational problems encountered by law enforcement officials are a regular agenda item. Through the three law enforcement agencies present at the meeting--the Houston Police Department, the Texas State Department of Public Safety, and the Harris County Sheriff's Office--operational problems are brought to the attention of other team members. Law enforcement personnel have noted problems such as signals that are not sufficiently visible to the public, locations where traffic is illegally using the freeway shoulder for travel lanes, and locations where speed zone information is needed. Where appropriate, the responsible agency has instituted measures such as additional signing and striping to correct the problems noted by law enforcement personnel.

Development of Interagency Technical Teams

At the monthly meetings, several issues are discussed that require an ongoing effort by a subcommittee of the team. The most notable of these issues is the better management of emergency incidents. In some cases, freeways that carry more than 200 000 vehicles/day have been closed for more than four hours due to incidents such as overturned trucks. A subcommittee of the team was formed to investigate means of improving traffic handling during such emergencies. At present, the subcommittee is considering the manpower and equipment requirements needed to create a major incident response team (MIRT). This special team might operate as a modified version of the MIRT currently operated by the California Department of Transportation. It could, for example, detour traffic upstream of a traffic-blocking incident to alternative routes. The team could temporarily modify signal operations, provide route information to the traveling public, close freeway entrance ramps immediately upstream of the incident, etc.

Other issues for which the team has set up interagency subcommittees are a review of freeway access violations, the joint application of recognized computer models to freeways and major thoroughfares, and a review of major accident locations. The participants in these subcommittees do not have to be designated team representatives. They can be, and are encouraged to be, other appropriate individuals from the member organizations.

OVERALL EVALUATION OF TEAM ACTIVITIES

Although it is very difficult for a group of individuals to evaluate the effectiveness of their efforts objectively, there are some noticeable signs of the positive impact that the team has had on the operation of existing transportation facilities in Harris County:

1. Team attendance, participation, and interest are at their highest level. This increased participation has developed as more rapport between the member agencies has been established and the "rolled-up-sleeve" atmosphere of the monthly meetings has unfolded.
2. The foundation of interagency cooperation created by the team has cut through the normal red tape typically involved in handling issues that involve more than one agency. For example, individuals with the highway agency now know whom to contact in the law enforcement agencies to ask for increased enforcement in highway construction areas when major problems arise. The law enforcement officials have called on other team members for their advice when traffic engineering expertise was needed to examine a particular problem.
3. Most important, the communication links among all transportation-related operational agencies in Harris County that have been established through the Houston Traffic Management Team will continue irrespective of actual representation on the team. This has led to an increased awareness of ongoing and proposed projects sponsored by each agency. An essential output of this is that different projects that affect the same traffic corridor can be handled so as not to work against each other. At each team meeting, project progress and potential conflicts are discussed so that appropriate adjustments can be made in a timely manner.

CONCLUSIONS

At the time this paper was written, the Houston Traffic Management Team had been meeting for more than a year and a half. It has successfully dealt with operational problems in existing transportation facilities. These problems include, but are not limited to, the evaluation of traffic control strategies for major urban freeway rehabilitation projects, the review of proposed operational improvements in existing transportation facilities, the operational problems encountered by law enforcement officials, and emergency incident management strategies. The participating agencies include representatives from TSDHPT, the Houston Traffic and Transportation Department, the Houston Fire Department, law enforcement agencies in Harris County, the Metropolitan Transit Authority, and the Texas Transportation Institute. It should be emphasized that participants act only to the extent of the operational authority they have within their own organizations--that the "team" does not "approve" anything.

RECOMMENDATIONS

We acknowledge that the approach of the Houston Traffic Management Team may not be appropriate for all major urban areas. It is suggested that such an approach be applied when the successful operation of existing transportation facilities crosses jurisdictional boundaries, as in Harris County. As this paper indicates, three law enforcement agencies have separate jurisdictions in Harris County: the City of Houston, Harris County, and the State of Texas. All have traffic enforcement responsibilities on the roadways in the Houston metropolitan area. In addition, although the Metropolitan Transit Authority has sole responsibility for all public transportation operations in Harris County, it must work closely with all of the above agencies to maintain an adequate level of service.

The primary role of the Houston Traffic Management Team, as stated previously, is to serve as an informal communication link between all transportation-related operational agencies in Harris County. This role will continue irrespective of the people now involved. Consequently, based on the success in Houston, this approach is recommended where a jurisdictional situation similar to that in the Houston metropolitan area exists.

REFERENCE

1. G. Sparks. San Antonio TSM Corridor Management Paper. Presented at 59th Annual Meeting, TRB, 1980.

Publication of this paper sponsored by Committee on Freeway Operations.

Development of an Interactive Planning Model for Contraflow Lane Evaluation

REGGIE J. CAUDILL AND NANA M. KUO

Work undertaken to develop an interactive computer simulation model for assessing the impacts of contraflow lane projects along existing freeway corridors is described. The methodology presented assembles existing, extensively used travel demand and traffic flow models into an integrated planning tool. The travel and flow characteristics of a corridor are processed, and the user is presented with a summary of the predicted changes. These submodels include the Greenshields linear speed-flow model, the California diversion model, and a multinomial and incremental logit model developed by Cambridge Systematics, Inc. The interactive nature of the package allows the transportation planner to perform the evaluation with a minimum of effort. An example based on data from Washington, D.C., is used for illustration.

As the population of a city grows, the streets and highways that once served it adequately become progressively more congested, and frustrating traffic jams and the associated loss of time and money become more and more common. The many ideas that have been proposed to resolve this problem have met with varying degrees of success. Preferential with-flow and contraflow lane projects are two solutions that have proved to require fewer initial capital investments than alternatives such as expanding fixed-guideway facilities, extending bus operations, or expanding other mass transit services.

A preferential with-flow traffic lane is a lane reserved usually for the use of designated multiple-occupant vehicles (buses, carpools, and vanpools). Although this solution may reduce traffic congestion for those who share rides, it may also increase the congestion experienced by other drivers since one less lane is available to them. Consequently, a preferential lane can sometimes aggravate the existing congestion problem.

A contraflow lane, on the other hand, appears to be a more promising solution. Because traffic patterns for modern American cities commonly are unidirectional during rush hours, little more than half of the city's freeway capacity is used during these peak times. Contraflow lanes help to relieve the traffic congestion during rush hours by appropriating the lane (or lanes) closest to the median from the minor traffic stream and designating these lanes for the use of the major flow stream. Because the direction of the major flow changes with the time of day, the lanes closest to the median on both sides are both contraflow lanes and are allowed to operate in the direction of the heaviest traffic during the daily peak periods. A contraflow lane does not require a major change in the established driving habits of the average trip maker and does not inconvenience those who do not participate in ridesharing or mass transit. In fact, contraflow lanes simply provide transit riders and carpoolers with faster and more dependable means of getting to their destinations.

Several case studies of existing contraflow projects have been published (1-3). However, there has been relatively little transportation literature discussing exactly how much, if any, improvement in vehicle and passenger flow could be expected from a contraflow installation. Most contraflow projects appear to have been implemented mainly to test out the idea rather than with the expectation of a prequantified improvement. This willingness to experiment with new ideas has contributed greatly to the volume of knowledge available about contraflow lanes, but it cannot be the most effective manner in which to decide whether a contraflow lane is the appropriate solution to a city's transportation problem.

The interactive computer simulation model presented in this paper is designed to help planners decide the feasibility of implementing a designated contraflow lane into an existing corridor by predicting some of the effects that might be expected from the installation of such a lane. The approach followed integrates existing, well-developed travel demand and traffic flow models into an interactive planning tool.

CONTRAFLOW LANES

When first implemented, contraflow lanes were often restricted to buses only. Today, many contraflow projects permit both buses and multiple-occupant vehicles to use the lanes. These projects directly encourage the use of carpools, vanpools, and transit by allowing the people who use transit and ridesharing to benefit from the lower traffic congestion and higher vehicle speeds in the contraflow lanes. Contraflow projects also have received more support from nonuser groups than projects that use preferential with-flow lanes because a decrease in the congestion experienced by multiple-occupant vehicles is not generally accompanied by an increase in the congestion experienced by those who drive alone (4).

Excessive weaving of vehicles is not as big a problem with contraflow lanes as it is with preferential with-flow lanes because there is more likely to be a lower speed differential between the contraflow and unrestricted lanes than between the with-flow and corresponding unrestricted lanes (5). The smaller speed differential may be traced to the fact that, where a contraflow lane opens up a new lane for the existing traffic, a with-flow preferential lane essentially denies an old lane to the traffic. However, this is not to say that contraflow lanes are completely accident free. In fact, problems do arise when vehicles enter and exit contraflow lanes. A case in point would be the carpool-bus bypass lane on the Moanalua Freeway, where "the most predominant types [of accidents] were sideswipes involving a vehicle in the carpool lane and another attempting to enter or leave the lane, and a single vehicle losing control and colliding with a fixed object, usually the median" (6). Contraflow lanes may increase the accident rate in the corridor, but the increase is often only comparable to that which would be experienced if an extra nondesignated traffic lane had been added and usually less than if a with-flow preferential lane had been installed. In fact, after the concurrent implementation of its contraflow and ramp-metering projects, the city of Houston experienced a decrease in the overall accident rate on Interstate 45 (7).

Contraflow lanes also tend to have fewer violation problems, possibly as a result of the relatively limited number of entrance and exit ramps and the fact that congestion on all of the lanes has been reduced (4).

However, contraflow lane projects do have their disadvantages. They are short-term solutions to a long-term problem in that they reduce the number of lanes available to the minor traffic stream, a traffic stream that will continue to increase with the population and ubiquity of the city. The design of the entrances and exits to the lane requires very careful formulation and implementation. The operation and control of the lane and driver behavior within the lane must be given continual attention because of the possibly disastrous consequences. Finally, additional considerations should be given to the design of shoulders to accommodate disabled contraflow vehicles. These drawbacks, among others, prompted the 1976 version of the Transportation and Traffic Engineering Handbook (8), which sets forth some guidelines to consider before proceeding with the installation of a contraflow lane:

1. The average speed of the freeway should decrease by at least twenty-five percent [during the trouble periods] over the normal speed or there should be a noticeable backup at signalized intersections leading to vehicles missing one or more green signal intervals; i.e., the demand should be greater than the capacity of the freeway.
2. The traffic congestion problem under investigation should be both "periodic and predictable."
3. The ratio of major to minor traffic counts should be at least two to one and preferably three to one. Otherwise, the installation of a contraflow lane could be the cause of a new traffic problem on the minor stream side of the freeway.
4. The contraflow lanes must be designed with adequate entrance and exit capacities in addition to easy transitions between the normal and the reverse flow lanes. Otherwise, the contraflow lane could be the cause of bottlenecks and other traffic problems in addition to the existing traffic congestion.

These guidelines provide general direction for the planner, but no procedure or methodology is suggested for estimating the impacts of a contraflow lane. The simulation model described in this paper provides the planner with a technical and interactive planning tool for quantitatively evaluating traffic flow improvements derived from the implementation of contraflow lanes. Its usefulness is directly related to the applicability of the travel demand and traffic flow submodels on which it is based.

CONTRAFLOW SIMULATION MODEL METHODOLOGY

The contraflow simulation model is an interactive computer package designed for a dual-screen work station consisting of an IBM/3277 display station model 2 (for alphanumeric input and output) and a TEKTRONIX 618 storage tube (for graphical input and output). The work station is linked to an IBM/3081 mainframe computer and uses the VM/370 operating system. The package can be used on any IBM-compatible full-screen terminal if the graphics are not required. The graphics are specifically designed to be displayed on a TEKTRONIX graphical attachment, but they can also be sent to a zeta 1453sx plotter if the user so desires.

The package was implemented in an interactive environment to allow the user to enter the necessary data with a great deal more ease and flexibility than is possible with a batch-operated system. For example, if a data entry error is detected in this interactive model, the user may correct the mistake without exiting from the simulation. In addition, with an interactive format the user is given the opportunity to perform multiple runs within a short period of time to determine the sensitivity of the results to specified variations in the model parameters.

The time requirement for running the simulation package is primarily related to the speed with which the data are entered. The IBM/3081 has a cycle time of approximately 26-28 nanoseconds, and the data manipulation occurs almost instantaneously after the initial data entry step. An average simulation requires, in central processing unit (cpu) time, approximately 0.6 s (without the graphics) to 1.98 s (with the graphics).

In the process of predicting the impact of a contraflow lane, the program performs a sequence of four basic tasks. Estimating the initial modal split is the first task. After the user enters the travel demand characteristics that correspond to each of the four population subgroups being considered, the program estimates the existing modal split by using a multinomial logit model developed by Cambridge Systematics, Inc. The second task in the sequence involves predicting the concentration level in the contraflow lane. This prediction is obtained by iteratively estimating the vehicle flow that will be diverted to the contraflow lane and solving the corresponding Greenshields equation for that flow.

The third task is to estimate the mean time delay, the sum of all of the time gaps that the average vehicle trying to enter the contraflow lane rejects before it is able to enter the lane. This calculation is based on the assumption that the traffic in the contraflow lane can be described by an Erlang distribution function. If the mean delay becomes too large, cars entering and exiting from the lane could be causing a new congestion problem in the main corridor. The fourth and final task is to tabulate all of the initial and final characteristics of the corridor for analysis. This final tabulation gives the user an overall view of the impacts that implementing a contraflow lane could have on the corridor being studied. A flowchart that describes the sequence of calculations performed by the program is shown in Figure 1.

Before entering the simulation, the user must compile a record of the characteristics of the corridor. These characteristics fall into four categories: (a) physical characteristics such as the number of lanes on the corridor, (b) traffic flow characteristics such as the existing and jam vehicle concentrations, (c) vehicle operating characteristics such as the number of passengers per vehicle, and (d) travel characteristics such as the trip lengths and trip times associated with the corridor. To give the user an idea of some typical parameter values, the first step in the simulation assigns the default flow and gap acceptance parameter values in addition to the travel characteristics of the area to the appropriate simulation variables. These flow and gap acceptance parameters, their abbreviations, their typical values (using the Washington, D.C., area as an example) and their units of measure are given in Table 1.

After the defaults have been assigned, the travel characteristics are written onto the MODESPLIT panel and displayed on the terminal as shown in Figure 2. A panel is a formatted alphanumeric display on a full-screen terminal that makes it possible to input and output an entire screen of data at one time instead of line by line.

The MODESPLIT panel is displayed four times, once for each population subgroup being considered in this simulation. These subgroups are those who have access to (a) transit only, (b) transit and shared

Figure 1. Methodology sequence.

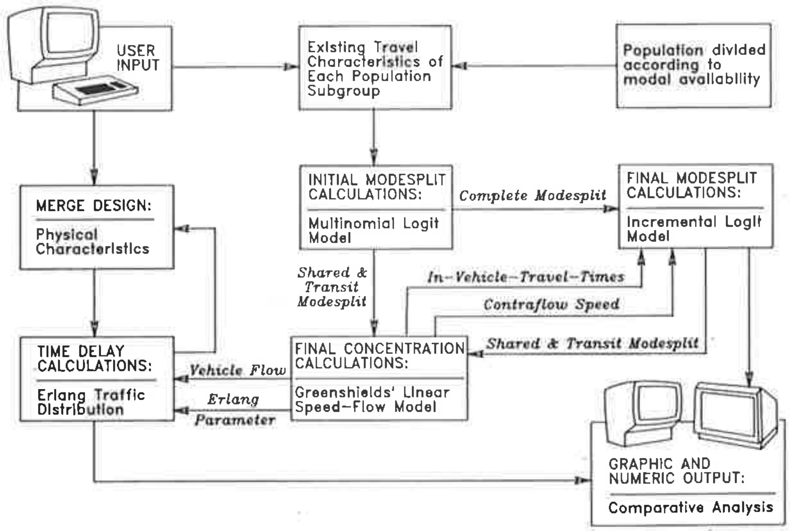


Figure 2. Travel characteristics.

DRIVE ALONE:	
OPTC (¢):	130.00
IVTT (minutes):	44.00
OVTT (minutes):	16.70
BW (1 TO 0):	.78
Disp. Income ($):	10400.00
Cars/Licensed Driver:	.90
SHARED RIDE:	
total OPTC (¢):	152.50
IVTT (minutes):	53.00
OVTT (minutes):	19.30
GW (1 or 0):	1.00
# Workers/household:	1.97
Employees/Comm. Acre:	107.00
Disp. Income ($):	10300.00
Cars/Licensed Driver:	.68
TRANSIT:	
OPTC (¢):	99.00
IVTT (minutes):	55.80
OVTT (minutes):	36.32

POPULATION SUBGROUP: TRANSIT, SHARED RIDE, AND DRIVE ALONE	
Fraction of Total Pop:	.62
Avg Household Income($):	13238.29
Avg Trip Length (miles):	8.19
INITIAL FLOW PARAMETERS:	
Number of lanes/side:	3.00
Free Flow Speed(mph):	55.00
Concentration/lane:	110.00
Jam Concentration:	140.00
Avg Shared Ride Load Size:	2.50
Avg Transit Load Size:	50.00
Frac of Trip in Line Haul:	.70
Diversion Rate to Cflow:	.90

Table 1. Parameters used in contraflow simulation.

Parameter	Typical Value	Abbreviation
No. of lanes	>3	-
Free-flow speed (mph)	55	V_f
Concentration (vehicles/mile)	110	K
Jam concentration (vehicles/mile)	140	K_j
Vehicle flow (vehicles/h)	1296	Q
Avg shared load (passengers)	2.50	L_s
Avg transit load (passengers)	50	L_t
Fraction of trip spent in line-haul	0.70	-
Diversion rate to contraflow lane	0.90	Div
Angle of merge (°)	2	-
Type of merge	Parallel	-
Length of acceleration lane (ft)	400	-

ride, (c) shared ride and drive alone, and (d) all three modes of travel. If the user does not choose to consider any of the four subgroups displayed, a value of zero may be indicated for the "fraction of total pop" variable. This option allows the planner to run the simulation by using aggregate data and specifying that the entire population has access to all three modes of travel. The user may also enter all the data for the existing travel characteristics for each subgroup requested by the panel or accept any of the default values shown on the panel. Once these values have been input, the initial modal splits are calculated by using the multinomial logit modal-split model proposed by Cambridge Systematics, Inc.:

$$P(i{:}A) = e^{U_i} / \sum_{m \in A} e^{U_m} \qquad (1)$$

where

m,i = travel mode alternatives,
A = set of possible choices,
P(i:A) = probability of choosing alternative i out of the set of available alternatives A, and
U_i = utility of alternative i.

The Cambridge Systematics model was used because it can handle more than two modes of transportation and because it includes a variable for in-vehicle travel time that would be affected directly by the installation of a designated contraflow lane (9).

The relative attractiveness of each mode in terms of its travel time, level of service, and cost-effectiveness is quantified by its utility function (9). The following utility equations for drive alone (Ud), shared ride (Us), and transit (Ut) were calibrated for the Washington, D.C., area by Cam-

Table 2. Travel characteristics parameters.

Parameter	Mode	Typical Value	Abbreviation
Round-trip out-of-pocket travel cost (¢)	D	130.00	OPTC
	S	152.00	
	T	99.00	
Round-trip in-vehicle travel time (min)	D	44.00	IVTT
	S	53.00	
	T	55.80	
Round-trip out-of-vehicle travel time (min)	D	16.70	OVTT
	S	19.30	
	T	36.32	
One-way trip distance (miles)		8.19	DIST
Automobile availability (cars/driver)	D	0.90	AALD
	S	0.68	
Breadwinner		0.78	BW
Destination in CBD		1.00	DCITY
Annual income ($)		13 238.29	INC
Annual disposable income ($)	D	10 400.00	DINC
	S	10 300.00	
Incentive programs		1.00	IP
Number of workers per household		1.97	NWORK
Employment density (employees/commercial acre)		107.00	DTECA

Note: D = drive alone, S = shared ride, T = transit.

bridge Systematics by using a least-mean-squares method:

$$Ud = -3.24 - (28.8 * OPTC/INC) - (0.0154 * IVTT) - (0.160 * OVTT/DIST) + (3.99 * AALD) + (0.890 * BW) - (0.854 * DCITY) + (0.000\,071 * DINC) \quad (2)$$

$$Us = -2.24 - (28.8 * OPTC/INC) - (0.0154 * IVTT) - (0.160 * OVTT/DIST) + (1.62 * AALD) + (0.287 * IP) - (0.404 * DCITY) + (0.000\,071 * DINC) + (0.0983 * NWORK) + (0.000\,65 * DTECA) \quad (3)$$

$$Ut = -(28.8 * OPTC/INC) - (0.0154 * IVTT) - (0.160 * OVTT/DIST) \quad (4)$$

Cambridge Systematics has done a number of tests on the transferability of these utility functions to cities other than Washington, D.C. (10). The travel characteristics used in these equations, their abbreviations, typical values, and units of measure are given in Table 2.

In these equations, OPTC/INC is defined as the round-trip out-of-pocket travel cost measured in cents divided by the total income measured in dollars. For the driver, the out-of-pocket travel cost (OPTC) includes the cost of gasoline, oil, lubrication, and maintenance in addition to travel tolls and parking charges. For the ridesharer, it is all of the above costs dispersed among the members of the carpool or the ridesharing group, and for the transit rider it would simply be the bus fare (11).

The effect of "different income groups valuing savings in cost differently" is reflected in the OPTC/INC term, which appears in the utility functions for all three modes (10). The inverse effect of income level on the bus modal share is reflected in the lack of a positive disposable income coefficient or variable (DINC) in the transit utility function. In the shared-ride and drive-alone utility functions, though, DINC is measured in dollars, and "for Washington, disposable income was defined as household income minus $800 times the number of persons in the household" (11).

IVTT is the round-trip in-vehicle travel time measured in minutes. The IVTT is defined as the time spent in actual transportation from the origin to the final destination and back again. For car drivers, this may be found by dividing the round-trip distance by the average trip speed (11). This includes the time spent picking up and dropping off riders and the time spent waiting when the bus stops for passengers to board and alight (11).

The excess time--the time spent walking to and from a parking lot or bus stop or waiting for and tranferring between buses--is accounted for in the level-of-service measure (OVTT/DIST), the round-trip out-of-vehicle travel time in minutes divided by the average one-way trip length in miles. The OVTT/DIST term reflects "the effect that a traveller making a short trip values savings in wait or walk time more than he or she would when making a long trip" (10).

The variable AALD is the variable for automobile availability, which appears only in the utility equations for shared riders and for people who drive alone. It is measured in terms of the number of automobiles available in a household divided by the number of licensed drivers in the household (11).

The variable BW indicates whether the tripmaker is the "breadwinner," the main source of income for the family. The variable DCITY is another indicator variable for the destination of the tripmaker [one if bound for the central business district (CBD) and zero otherwise]. For this simulation, DCITY was implicitly taken to be one because, in most cities that experience heavy periodic and unidirectional traffic congestion during the morning peak hour, a majority of the traffic is destined for the CBD. It should be noted that DCITY contributes negatively to the utility functions of the shared-ride and drive-alone modes. This is to account for the "congestion and the inconvenience associated with driving into the CBD in large cities" (11).

The variable IP is designed to "reflect the effect of large organizations offering carpool incentives" (11). In the Washington, D.C., area, the large organization was taken to be the government, and thus IP was interpreted to be one if the majority of the population subgroup were government employees and zero otherwise. However, generally the user should enter a one (1) for IP only if there are a large number of sizeable employee incentive programs in the CBD and a zero (0) otherwise. The variable NWORK is the average number of workers in the average household, and DTECA is the employment density in the work zone, "the number of employees divided by [the] commercial area in acres" (11). Travel costs must be entered in cents, incomes in dollars, and times in minutes.

When all of the average travel characteristics of each population subgroup have been entered, the program calculates the utility of each mode for each of the four population subgroups. These utilities are then used to find the corresponding modal splits, which are then normalized over the entire population. Next, the program iteratively estimates the vehicle concentrations for the contraflow as well as for the unrestricted traffic lanes. To date, little research has been done in estimating the concentration on the unrestricted lanes after the implementation of the contraflow lane. However, a reasonable assumption is that the concentration will not be reduced significantly by the removal of the multiple-occupant vehicles. In fact, the Houston I-45 contraflow project has reported "negligible impacts on peak-direction traffic volumes and travel speeds" (3). During a rush hour, the buses and carpools diverted to the contraflow lanes are replaced by other single-occupant vehicles. Consequently, the concentration in the unrestricted lanes is assumed to remain constant.

The contraflow concentration, on the other hand, is determined by estimating the original shared-ride and transit vehicle flow and assigning a fraction (the diversion rate) of this flow to the contraflow lane. The corresponding concentration is found by solving for the larger real root of the quadratic equation derived from the Greenshields linear speed-flow model. The Greenshields model is as follows:

$$Q = K * Vf(1 - K/K_j) \tag{5}$$

where Q is the fraction of original multiple-occupant vehicle flow (vehicles/h) and the other terms are as previously defined. The quadratic equation derived from the Greenshields model is as follows:

$$0 = K^2 - (Kj)K + (Q * Kj/Vf) \tag{6}$$

Not all of the original bus and shared-ride flow is assumed to be diverted into the contraflow lane for the following reasons:

1. The entire length of the trips will not be spent in the contraflow lane.
2. Some trips may not be long enough to warrant the use of the contraflow lane.
3. The vehicles using the contraflow lanes must weave across the freeway when entering and exiting.

Consequently, some adjustment factor is necessary and is estimated by using the California diversion formula and setting the distance saved from using a contraflow lane equal to zero (12). The California diversion formula is as follows:

$$P = 50 + 50(d + 0.5t)/\sqrt{[(d - 0.5t)^2 + 4.5]} \tag{7}$$

where

P = percentage of trips via contraflow,
d = distance saved (miles), and
t = time saved (min).

From the estimate of the contraflow concentration, a new speed and the corresponding in-vehicle travel time (IVTT) are found by using the following relations, which are also derived from the Greenshields linear speed-flow model (Equation 5):

$$V = Vf(1 - K/Kj) \tag{8}$$

and

$$IVTTnew = IVTTold[(1 - p) + (p * Vold/Vnew)] \tag{9}$$

where p is the fraction of the total trip length spent on the line-haul portion of the freeway.

To reduce the data requirements, an incremental logit model is used to calculate the new modal split based on the new IVTT. With this new modal split, the iterative process continues until the most recent estimate of the concentration differs from the previous estimate by not more than 1 percent, which usually takes three or four iterations. At this point, the new modal split is displayed and the Erlang parameter that describes the variability of the speed distribution in the contraflow lane is calculated. In lieu of a more reliable method, the assumption has been made that the traffic volume is distributed linearly with the Erlang parameters. To find the appropriate Erlang parameter, the program first divides the flow capacity (2000 vehicles/h) into six equally spaced ranges and matches each range with an Erlang parameter. The parameter ranges from one if the traffic in the contraflow lane is truly random and the volume is equal to zero to six if the traffic volume is approaching the capacity of the contraflow lane (13). Finally, the contraflow volume is compared with these ranges and the corresponding Erlang parameter is assigned.

Next, the simulation proceeds to display the initial and final speeds as well as the contraflow concentration and the Erlang parameter. The user then enters the following design parameters for the merge between the unrestricted and the contraflow lanes: (a) the jam concentration, (b) the angle at which vehicles will be allowed to merge into the contraflow lane, (c) the type of merge (one for taper and zero for parallel), and (d) the length of the acceleration lane in units of 100 ft. These parameters are used to calculate the critical time gap, the mean delay, and the variance of the delay by using formulas based on the assumption that the gaps in the contraflow lane have an Erlang distribution (13). The Erlang distribution function, Erlang mean delay function, and Erlang variance function, respectively, are given below:

$$f(t) = [(aQ)^a/(a - 1)!]\, t^{(a-1)}\, e^{-(aQt)} \tag{10}$$

$$\mu(t)_a = \left\{ e^{(aQT/3600)} - \sum_{i=0}^{a} [(aQT/3600)^i/i!] \right\} /Q \sum_{i=0}^{a-1} [(aQT/3600)^i/i!] \tag{11}$$

$$\sigma^2(t)_a = \left[\left((a + 1) \left\{ e^{(aQT/3600)} - \sum_{i=0}^{a+1} [(aQT/3600)^i/i!] \right\} \right) \div \left\{ aQ^2 \sum_{i=0}^{a-1} [(aQT/3600)^i/i!] \right\} \right] + \mu^2(t)_2 \tag{12}$$

where

a = Erlang parameter,
T = critical time gap (h), and
t = time gap (s).

In these calculations, delay refers to the sum of all time gaps that a vehicle attempting to merge into the contraflow lane will reject before it finds one large enough for it to accept. The mean delay and the variance of the delay are statistics that give the user some indication of the state of the queuing process that is being experienced by the vehicles attempting to get into the contraflow lane. If the mean delay and the variance become too large, one may surmise that the merging procedure is not proceeding smoothly and that the queue of vehicles trying to get into the contraflow lane could be causing more traffic congestion than the contraflow lane is relieving. These characteristics of the merging process, shown in Figure 3, are displayed on the terminal.

Once the delay has been calculated, the new passenger flow can also be found by multiplying the vehicle flows by the different modal splits and the corresponding load factors and vehicle size adjustment factors. These calculations are performed by assuming that only a fraction of the total multiple-vehicle flow will occur in the contraflow lane. This will be the same fraction, the diversion rate, that was calculated previously. Therefore, new modal splits for the unrestricted lanes must be determined. The new modal share for the (i)th mode in the unrestricted lanes is estimated by using the following equation:

$$M(i) = MSPLIT(i)/\left\{ MSPLIT(D) + (1 - Div)\, [MSPLIT(S) + MSPLIT(T)] \right\} \tag{13}$$

where M(i) is the modal split to the (i)th mode and (i) equals (D)rive alone, (S)hared ride, (T)ransit. Similarly, a new modal split for the contraflow lane needs to be estimated, and this is accomplished by using the following equation:

$$M(i) = MSPLIT(i)/[MSPLIT(S) + MSPLIT(T)] \tag{14}$$

where M(i) is the modal share to shared ride or transit and (i) equals (S)hared ride, (T)ransit.

Figure 3. Contraflow merge characteristics.

```
+------------------------------------------------------------------+
|                                                                  |
|    INTIAL CONCENTRATION:       110 VEH/MIL                       |
|    OLD SPEED:   12 mph   NEW SPEEDS:   22 mph   12 mph           |
|                                                                  |
|    E[Contraflow lane concentration]                       90     |
|    E[Unrestricted lane concentrations]                   110     |
|    Angle of Merge ( in degrees )                           2     |
|    Type of Merge (0=parallel, 1=taper)                     0     |
|    Length of Accel Lane (100's of feet)                    4     |
|    Erlang Parameter                                        5     |
|    (1 to 6 = random to stalled traffic)                          |
|                                                                  |
+------------------------------------------------------------------+
|                                                                  |
|        CRITICAL TIME GAP (seconds):                        4     |
|        MEAN DELAY (seconds):                              28     |
|        VARIANCE OF DELAY (seconds):                      169     |
|                                                                  |
+------------------------------------------------------------------+
Type Y to respecify merge parameters, and N otherwise.
```

Finally, the new passenger flows are given by the following equations:

$$CPV = \left\{CFLOW[(LFS * SSPLITc) + (LFT * TSPLITc/1.6)]\right\} \div (SSPLITc + TSPLITc) \quad (15)$$

$$UPV = RFLOW[(LFD * DSPLITr) + (LFS * SSPLITr) + (LFT * TSPLITr/1.6)] / DSPLITr + SSPLITr + TSPLITr \quad (16)$$

where

CPV = contraflow passenger volume (passengers/h),
UPV = unrestricted passenger volume (passengers/h),
CFLOW = contraflow vehicle flow,
RFLOW = unrestricted vehicle flow,
LFD = drive-alone load size = 1,
LFS = shared-ride load size,
LFT = transit load size,
DSPLITr = modal share to drive alone,
SSPLITr = modal share to shared ride in unrestricted lanes,
TSPLITr = modal share to transit in unrestricted lanes,
SSPLITc = modal share to shared ride in contraflow lane, and
TSPLITc = modal share to transit in contraflow lane.

The 1.6 factor in the transit calculations is to adjust for the size of a bus (i.e., one bus is approximately 1.6 vehicle equivalents) (14).

Once all of the calculations have been performed, the pertinent flow characteristics of the freeway before and after the installation of the contraflow lane are displayed in tabular and graphical forms. The panel with alphanumeric data is shown in Figure 4, and the graphic display is shown in Figure 5. The comparison of the initial and final corridor characteristics offers the user a variety of criteria by which to judge the feasibility of implementing a contraflow lane. By running several simulations with different initial concentrations, the user could also judge what the minimum initial concentration would have to be to justify the use of a contraflow lane.

SIMULATION EXAMPLE

A sample simulation was performed with the typical parameter values indicated earlier in this paper. The simulation used the average travel demand characteristics of work trips in the Washington, D.C., area and reasonable estimates of the existing and jam concentration and various other physical design and flow parameters for a hypothetical corridor. The panels and graphs with the parameter values used in the simulation are shown in Figures 2-5.

This particular simulation predicts that the average speed over the hypothetical corridor will increase from about 12 to 15 mph if a contraflow lane were installed in the example corridor. This increase in the average speed in the corridor would also be accompanied by a decrease in average concentration from 110 to 104 vehicles/mile; an increase in the total vehicle flow from 3889 to 5655 vehicles/h; an increase in the total passenger flow from 25 669 to 26 802 passengers/h; a redistribution of modal split toward shared ride and transit; and a decrease in the in-vehicle travel time from 48 to 40 min. These statistics appear to confirm the hypothesis that contraflow lanes can contribute to a significant improvement in the level of service in the corridor. In particular, a contraflow lane can greatly increase the total passenger flow that the corridor can handle.

To determine the correlation between the change in passenger flow and the initial concentration level, a series of simulations was run. The initial concentration was varied in increments of 5 vehicles/mile while the physical parameters, flow parameters, and travel characteristics were kept constant. The results of these simulations are shown in Figure 6. As the graph in Figure 6 shows, the introduction of a contraflow lane can lead to a dramatic increase in passenger flows when the initial concentration is close to the jam concentration.

SUGGESTIONS FOR FURTHER RESEARCH

This paper investigates the effect of contraflow projects only in the major flow direction. Further work will be done to evaluate the effect of contraflow projects in the minor flow direction. This work could help the planner to estimate the expected useful life of the contraflow project before the lanes in the minor flow direction become too congested to allow the contraflow lane to continue operation.

Additional work should also be done to investigate the choice of transportation models used in this simulation and to calibrate these models by using real-life case studies. This research will serve to validate the predictions obtained from this simulation.

CONCLUSIONS

Contraflow lanes appear to be a promising solution

Figure 4. Numerical summary of results.

CHARACTERISTICS:	INITIAL	FINAL
SPEED (miles/hour) (C)ontraflow:		22
(U)nrestricted:	12	12
AVERAGE SPEED PER LANE:	12	15
CONCENTRATION (veh/mile/lane) C:		90
U:	110	110
AVERAGE CONCENTRATION PER LANE:	110	104
VEHICLE FLOWS (veh/hr/lane) C:		1766
U:	1296	1296
(total vehicles/hour):	3889	5655
PASSENGER FLOWS (pax/hr/lane) C:		22182
U:	8556	1540
(total passengers/hour):	25669	26802
NORMALIZED MODESPLITS (Drive Alone):	52	46
(Shared Ride):	30	34
(Transit):	17	19
NORMALIZED IVTT (minutes):	48	40

Figure 5. Graphical summary of results.

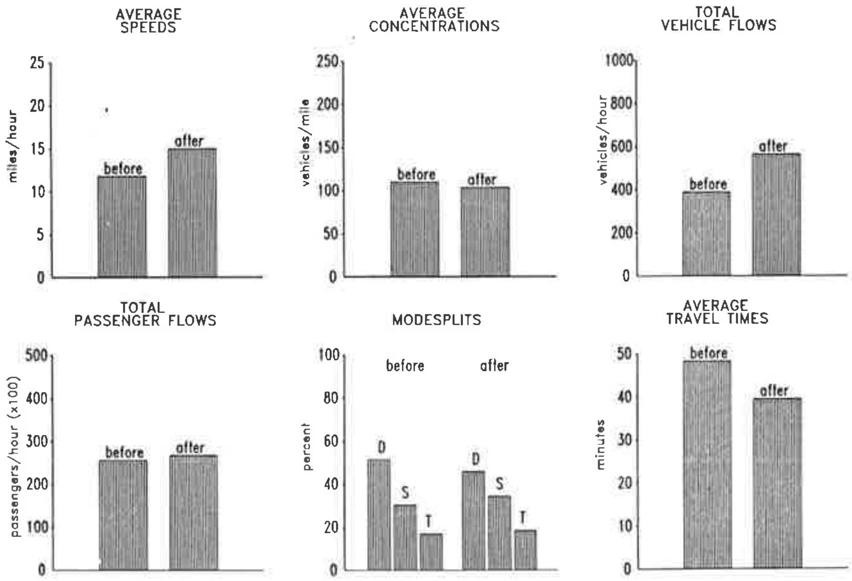
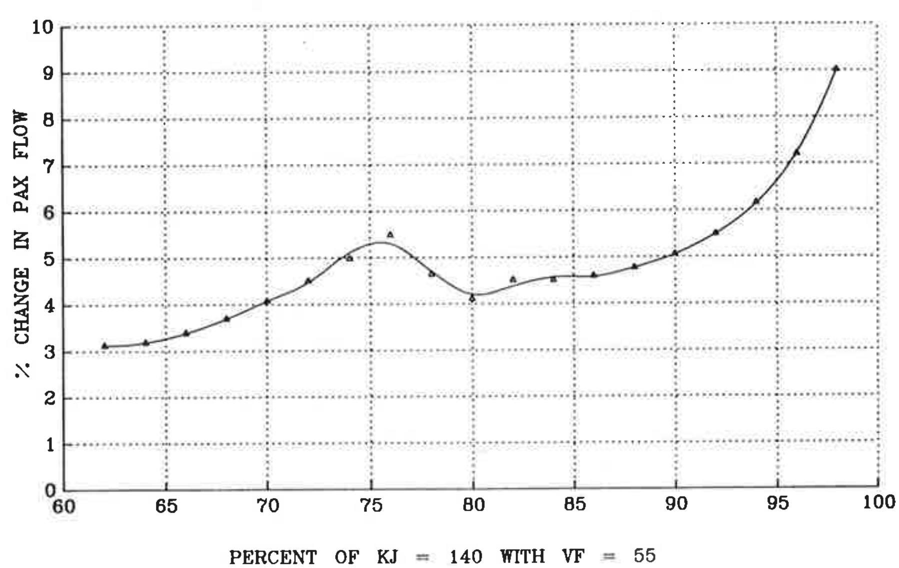


Figure 6. Changes in passenger flow versus initial concentration levels.



to traffic congestion in urban areas. If traffic congestion has been a sustained and periodic problem in a corridor, then the introduction of a contraflow lane could significantly improve the passenger flow in the corridor. The simulation program presented in this paper provides an effective method for the transportation engineer to test the feasibility of such a lane. The interactive nature of the program allows the planner to perform the evaluation with a minimum of effort. In particular, the graphical as well as numerical summary of results easily allows the planner to compare initial and final traffic conditions.

The accuracy of this approach depends on the accuracy of each of the associated travel demand and traffic flow submodels on which it is based. These submodels, although far from perfect, have been tested and used extensively over the past 20 years. The methodology described in this paper should have comparable usefulness as a planning tool for assessing the impacts of contraflow lanes.

REFERENCES

1. D. Kaku, W. Yamamoto, F. Wagner, and M. Rothenberg. Evaluation of the Kalanianaole Highway Carpool/Bus Lane. Offices of Research and Development, FHWA, Rept. FHWA-RD-77-100, Aug. 1977.
2. H.S. Rose and D.H. Hinds. South Dixie Highway Contraflow Bus and Carpool Lane Demonstration Project. TRB, Transportation Research Record 606, 1976, pp. 18-22.
3. R.N. Taube and C.A. Fuhs. Houston's I-45 Contraflow Transit Project. TRB, Transportation Research Record 798, 1981, pp. 39-45.
4. J.W. Billheimer. The Santa Monica Freeway Diamond Lanes: Evaluation Overview. TRB, Transportation Research Record 663, 1978, pp. 8-16.
5. J.W. Billheimer. The Santa Monica Freeway Diamond Lanes: Freeway Accident Analysis. TRB, Transportation Research Record 663, 1978, pp. 1-7.
6. D. Kaku, W. Yamamoto, F. Wagner, and M. Rothenberg. Evaluation of the Moanalua Freeway Carpool/Bus Bypass Lane. Offices of Research and Development, FHWA, Rept. FHWA-RD-77-99, Aug. 1977.
7. Cambridge Systematics, Inc. Houston North Freeway Contraflow Lane Evaluation Technical Memorandum: Summary of Pre-Contraflow Conditions. Transportation Systems Center, U.S. Department of Transportation, Cambridge, MA, Aug. 1980.
8. Institute of Traffic Engineers. Transportation and Traffic Engineering Handbook. Prentice-Hall, Inc., Englewood Cliffs, NJ, 1976.
9. Cambridge Systematics, Inc. Guidelines for Travel Demand Analyses of Program Measures to Promote Carpools, Vanpools, and Public Transportation. Office of Energy Conservation and Environment, Federal Energy Administration, Nov. 1976.
10. Cambridge Systematics, Inc. Tests of Transferability and Validation of Disaggregate Behavioral Demand Models for Evaluating the Energy Conservation Potential of Alternative Transportation Policies in Nine U.S. Cities. Office of Energy Conservation and Environment, Federal Energy Administration, April 1977.
11. T. Atherton. Approaches for Transferring Disaggregate Travel Demand Models. Department of Civil Engineering, Massachusetts Institute of Technology, Cambridge, Master's thesis, Feb. 1975.
12. R.J. Paquette, N. Ashford, and P.H. Wright. Transportation Engineering Planning and Design. Ronald Press Co., New York, 1972.
13. D.R. Drew. Traffic Flow Theory and Control. McGraw-Hill, New York, 1968.
14. L.J. Pignataro. Traffic Engineering: Theory and Practice. Prentice-Hall, Inc., Englewood Cliffs, NJ, 1973.

Publication of this paper sponsored by Committee on Freeway Operations.

Abridgment

Garden State Parkway HOV Lane

JOHN C. POWERS

Operation of a lane reserved for high-occupancy vehicles (HOVs) in each direction along 12 miles of the Garden State Parkway was studied. The HOV lane was established in November 1980 by addition of a lane in each direction to the existing six-lane divided and controlled-access roadway. Peak-period traffic flows before the addition of the HOV lane were characterized by levels of service D, E, and F along 5 or more miles of the road section that was widened. Information on numerous weekday peak-period traffic characteristics collected during the first year of HOV lane operation is reported. The definition of a carpool changed from three or more to two or more occupants in June 1981. A number of comparisons are presented for the two 6-month periods as well as for data collected before the HOV lane operation. Traffic before and after addition of the HOV lane was monitored for impacts of the HOV lane on HOV use, HOV and non-HOV travel time, automobile occupancy, person throughput, accident experience, HOV lane violations, and vehicle speeds. Results in terms of travel time, persons using HOVs, and accident data are reported.

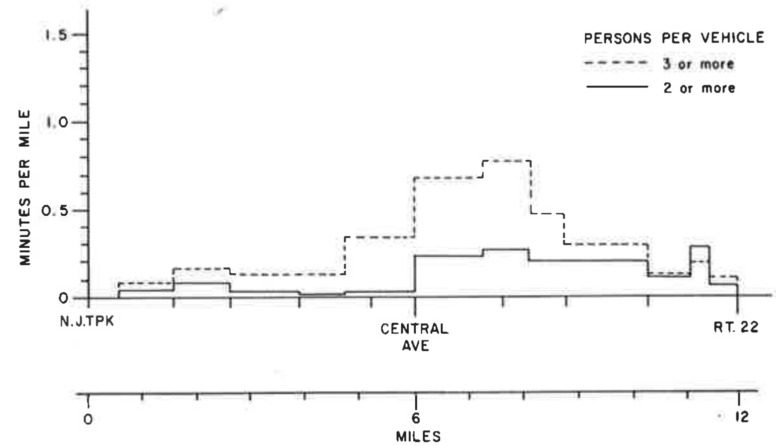
In November 1980, the newly added median lanes of each direction of travel on a 12-mile section of the Garden State Parkway were opened as concurrent-flow, continuous-access, high-occupancy-vehicle (HOV) lanes. The minimum occupancy level was set at three or more persons.

In June 1981 the carpool definition was reduced to two or more persons, and in June 1982 the restrictions were lifted entirely. This paper reviews and summarizes travel time, HOV use, and accident data collected during the first 12 months of HOV lane operation.

TRAVEL TIME SAVINGS

Comparisons of speeds in the reserved and unreserved lanes during the three-or-more operation revealed that HOVs saved more than 0.7 min/mile when congestion occurred during the northbound morning peak period (see Figure 1). At typical congestion levels during this peak period, the savings averaged as much as 3.2 min for the full length of the HOV

Figure 1. Typical time savings during northbound morning peak period.



lane. A travel time savings of as much as 1.3 min/mile occurred in the most-often-congested sections during the southbound evening peak period (not shown). At typical congestion levels during this peak period, the savings averaged as much as 5.1 min for the full length of the HOV lane.

Comparisons of speeds in the reserved and unreserved lanes during the two-or-more operation reveal that HOVs saved as much as about 0.3 min/mile in the most-often-congested sections in the northbound morning peak period. As a result of the relatively low congestion levels during this period, the savings averaged 0.9 min for the full length of the HOV lane during the morning peak period.

Comparisons of speeds in the reserved and unreserved lanes indicate that HOVs saved up to 0.4 min/mile in the most-often-congested sections in the southbound evening peak period. As with the morning peak period, relatively low congestion levels resulted in time savings of about 0.8 min for the full length of the HOV lane during the evening peak period.

HOV USE

Data collected in all lanes indicate that the percentage of persons traveling the Garden State Parkway northbound in the morning peak in HOVs increased by one-third from December 1980 to May 1981. The May percentage of persons carried in HOVs was four-fifths of the 1976 summer occupancy percentage but 110 percent of the 1980 summer occupancy percentage. The following table summarizes these data (in June 1981 the definition of an HOV changed to two or more persons):

	Persons Using HOVs (%)	
Time	Morning	Evening
Summer 1976	19	25
August 1980	13	21
December 1980	11	NA
May 1981	15	17
June 1981	35	49
August 1981	36	53
October 1981	31	42
November 1981	33	NA

After the change to two-or-more operation, the percentage of persons traveling the Garden State Parkway in HOVs declined to about 33 percent in November (just less than the June percentage of 35 percent) after peaking at almost 38 percent in July. During the peak hour the percentage reached nearly 40 percent, some 15 percent higher than the portion of the road reserved for HOV persons. Of these, the portion of persons in HOVs who used the HOV lane was observed to range from one-half to four-fifths after June and was as much as 31 percent of all persons on the roadway.

No comparisons are available for November, December, and January in the southbound evening peak because darkness prevented HOV counts during all or part of the hours between 4:00 and 6:00 p.m. Available data indicate that the percentage of persons traveling the Garden State Parkway in HOVs was two-thirds of the 1976 summer occupancy percentage and four-fifths of the 1980 summer occupancy.

Data for the evening peak period collected in all lanes after the change to two-or-more operation indicate that the percentage of persons traveling the Garden State Parkway in HOVs declined in October, the last month of evening data, at about 42 percent (about 6 percent lower than the 48 percent observed in June) after peaking at almost 53 percent in August. During the peak hour, percentages exceeded 56 percent, more than double the portion of the road reserved for HOV persons. The portion using the HOV lane was observed to range from two-fifths to one-half and was as much as 27 percent of all persons on the roadway.

Figure 2. Accident rates.

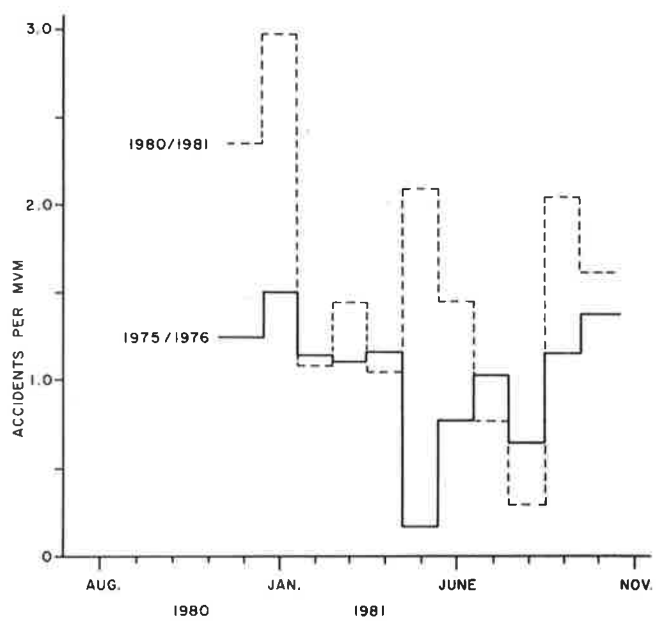


Figure 3. Volume changes during northbound morning peak period.

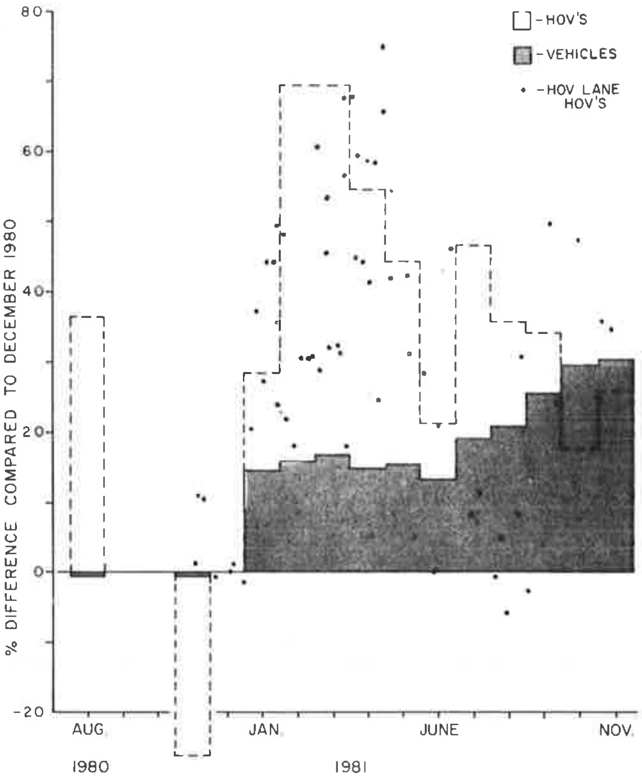
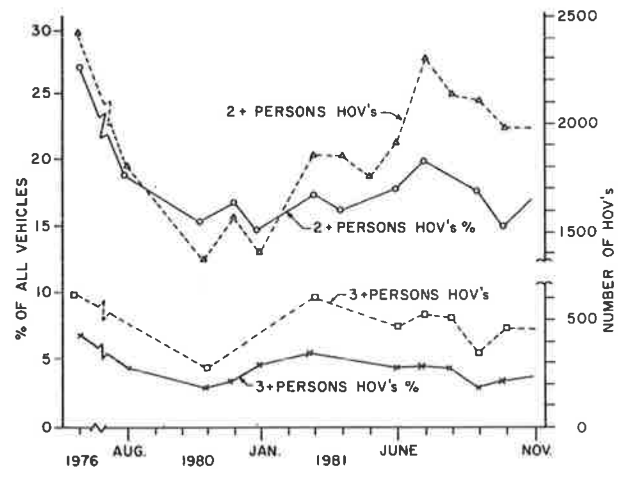


Figure 4. HOV volumes.



ACCIDENTS

The peak-period accident rates (see Figure 2) in the HOV lane section increased by as much as 100 percent to 2.97 accidents/million vehicle miles during the first two months of operation in comparison with a rate of 1.49 accidents/million vehicle miles for the same time of year in the before period of 1975-1976. Initial increases of this type have been observed on other highways where HOV lanes have been implemented. After January, peak-period accident rates in the HOV lane section declined, ranging up to 1.61 accidents/million vehicle miles. (The rates in the before period ranged up to 1.49 accidents/million vehicle miles.) Such a drop to preconstruction rates has been observed in successful HOV lane operations elsewhere.

Accidents increased from 66 to 109 in the HOV lane section (16 of these 43 accidents occurred in the first two full months) compared with an increase from 28 to 34 in a control section.

SUMMARY AND CONCLUSIONS

Although many measures were monitored for change during the study period, the basic yardstick for success was the number of HOVs. Any nonseasonal increase in the HOV percentage was accepted as a positive indicator. Although no specific share was set as a goal, a continually improving percentage was considered to be of primary importance.

Figures 3 and 4 show HOV volumes, their percentage of total volume, and the relative changes that occurred during the 12 months studied for the morning period. The evening data, which are not shown, are similar.

It was concluded that, with the exception of March 1981, changes in HOV volumes were highly related to substantial overall increases in demand, due largely to the additional capacity made available by widening (initially) and further by reducing carpool occupancy (in June 1981). It was also concluded that changes in HOV percentage, again with the exception of March 1981, were highly related to normal seasonal variations.

As expected, the addition of two-person vehicles as HOVs substantially reduced the congestion that occurred in the unreserved portions of the roadway during the first six months of operation. In fact, three years of average general growth in traffic volume would need to occur before peak volumes of unreserved-lane vehicles would be large enough to more than fill the unreserved portion of the roadway and subsequently cause increased congestion. In addition, as expected, the portion of vehicles eligible for HOV lane use exceeded the portion of the roadway reserved for them during the summer months. There were differences but, based on the comparative data collected one year apart (only several common points in the 15 or 16 months since August 1980), the Garden State Parkway and NJ-287 (the control site) changed little both before and after June 1981.

ACKNOWLEDGMENT

The contents of this paper reflect our views, and we are responsible for the facts and the accuracy of the data presented. The contents do not necessarily reflect the official views or policies of the New Jersey Department of Transportation or the Federal Highway Administration. This report does not constitute a standard, specification, or regulation.

Publication of this paper sponsored by Committee on Freeway Operations.

First-Generation UTCS Simulation

AMIR EIGER AND SHIH-MIAO CHIN

The development of an urban traffic control system (UTCS) simulation program that comprises the first-generation UTCS software (extended version) and a network traffic simulation model (NETSIM/ICG) is described. The simulator provides pseudo-real-time graphic displays of surveillance data and system performance measures in addition to the printed outputs of both the UTCS software and the NETSIM model. It can simulate both automated and manual modes of control. The development of the simulator supports current and future research in urban traffic control systems, provides a tool for evaluation before implementation of these systems, and is potentially useful as a training aid for UTCS operators.

Urban street traffic volumes exhibit fluctuations that necessitate signal control systems capable of appropriately adapting to the changing demand conditions. To date, several generations of such computerized urban traffic control systems (UTCSs) have been developed and implemented. These systems are centralized control systems that gather field data on traffic volumes and network link occupancies from vehicle detectors (sensors); on the basis of that information, they alter the signal settings at intersections in order to aid traffic flow. UTCSs can be described by a functional block diagram such as the one shown in Figure 1.

FIRST-GENERATION CONTROL STRATEGY

In implementing a first-generation control (1-GC) system, a set of timing plans is generated off-line and stored in computer memory in the form of a timing plan library. Corresponding to each timing plan is a plan signature, given by

$$\underline{S}_j = (s_{j1}, s_{j2}, \ldots, s_{jn}) \tag{1}$$

where s_{ji} is the design value of the traffic flow parameter(s) on link i for plan j. During the operation of the system, individual timing plans are selected for implementation either by time of day (TOD), traffic-responsive (TRSP), or manual (MAN) modes of operation. In the TRSP mode, timing plan selection is based on the computed deviations of the timing plan signatures from the actual signatures derived from field detector data. Thus, corresponding to each library plan there is a computed deviation:

$$D_j = \sum_i f(s_{ji} - v_i) \tag{2}$$

where v is the measured value of the flow parameter and f( ) is a measure of distance. Furthermore, in most current systems,

$$v_i = \mathrm{vol}_i + \mathrm{weight} \times \mathrm{occupancy}_i \tag{3}$$

The selection algorithm is essentially twofold:

1. The alternative plan with the minimum signature deviation is considered for implementation.
2. The existing plan is retained if its signature deviation is within some threshold percentage value of the minimum deviation.

Most 1-GC systems also include a critical intersection control (CIC) feature that enables split adjustment on a cycle-by-cycle basis.

This paper reports on the development of a first-generation UTCS simulator that has been developed as part of an overall program to investigate various aspects of 1-GC operation, including (a) the effectiveness of manual intervention, (b) evaluation of CIC control, and (c) operation during transition periods. In addition, the simulator is potentially useful as a training aid for UTCS operators and may be used to investigate emergency vehicle routing strategies.

UTCS SIMULATOR

With reference to Figure 1, the UTCS simulator must have the capability to appropriately simulate the system control mechanism, the operation of the signals and signal controllers, the traffic movements generating the detector data, and operator control and display. Figure 2 shows the general framework of the simulator.

Traffic Simulation Module

The traffic simulation module is the Network Simulation-Interactive Computer Graphics (NETSIM/ICG) model (1), an enhanced version of the NETSIM model originally developed for the Federal Highway Administration (2).

Figure 1. UTCS functional block diagram.

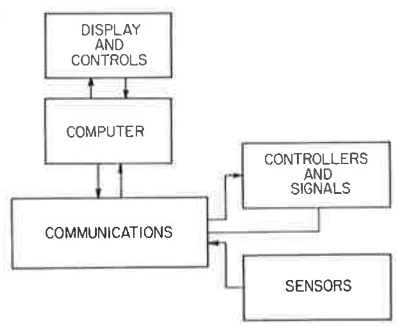


Figure 2. Description of UTCS simulator.

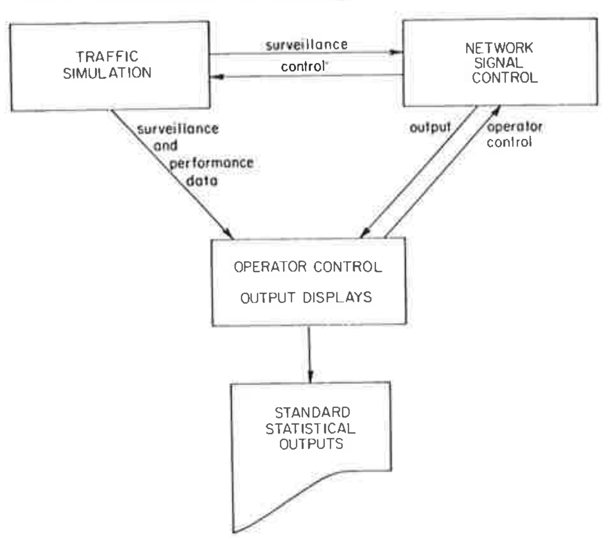


Figure 3. Dual-screen graphics workstation.

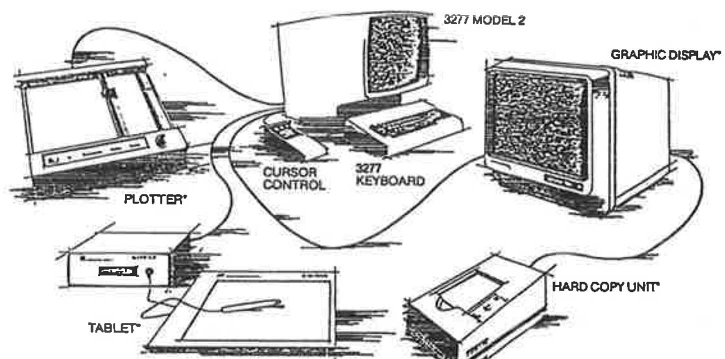
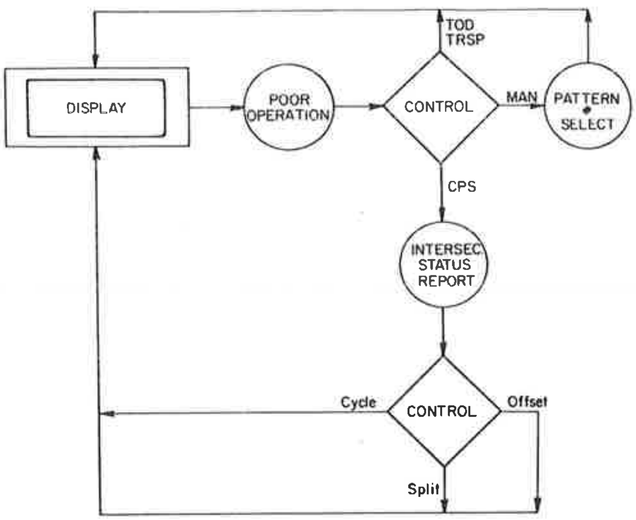


Figure 4. Procedural diagram for manual intervention.



NETSIM is the time-based microscopic traffic simulation program in which each vehicle traversing the network is treated as a separate entity. Its motion is governed by a set of microscopic car-following, queue discharge, and lane-changing algorithms. All vehicles are processed once every second, their positions are updated, and statistics are accumulated.

A variety of traffic controls can be imposed on this network. Intersection controls may take the form of STOP or YIELD signs; simple, fixed-time traffic signals operating either independently or as part of a coordinate system; and vehicle-actuated signals. As many as nine different signal phases can be incorporated in any given signal cycle. Detectors can be located at various points within any one link, with a maximum of three in any one lane.

Network Signal Control Module

The network signal control module is a modified version of the UTCS software (extended version) as implemented in Charlotte, North Carolina (3). The primary function of the control module is to command the traffic signal controllers through defined timing sequences.

The signal control module provides for selection and implementation of predefined signal timing plans in one of three modes: MAN, TOD, and TRSP. In the MAN mode, the operator specifies the number of the signal timing plan that he or she wants to impose on the signal network. In the TOD mode, the control module automatically selects and sets traffic signal timing plans in accordance with a predefined sequence organized by the day of the week and the time of the day (data input). In this mode, signal timing plans can be selected automatically as often as every 15 min. In the TRSP mode, the control module automatically selects the predefined traffic signal timing plan that is best suited to accommodate the current traffic flow conditions in the signal network as generated by the traffic simulation module. Pattern selection and implementation are accomplished through a traffic flow data matching technique that is executed every 15 min on the quarter-hour mark.

Three other modes of system control are provided and can be selected by the operator: off-line, critical intersection control, and controller parameter set (CPS). In the off-line mode, no communication (i.e., data transfer) is maintained between the control module and the traffic simulation. The controllers will operate in accordance with the signal logic in the traffic simulation module. In the critical intersection control mode, controller splits are adjusted once per cycle at controllers that are instrumented for critical intersection control. The split at any controller is apportioned according to the ratio of traffic demands on the conflicting intersection approaches. In the CPS mode, the operator may specify the cycle length, split, and offset of a particular controller. The controller will operate at the specified control parameters until the CPS is released and a new signal timing plan is called for by a MAN, TOD, or TRSP mode signal timing plan selection process.

Interface Between Network Control and Traffic Simulation

The interface between the NETSIM and UTCS modules is through two routines that emulate the communication function shown in Figure 1. The first routine essentially translates and transfers the controller timing commands generated by the UTCS module to the appropriate signal indication codes needed by the NETSIM module. This is done for all controllers that are under network control. The function of the second interfacing routine is to determine for every detector whether a vehicle has crossed that detector during the previous 1-s time step and, if so, transfer that information to the UTCS module, where the appropriate volume and occupancy counters are updated.

Operator Control and Visual Display Capabilities

The UTCS simulator was developed on an IBM 370/3033 with graphics attachment system (see Figure 3). It has the capability to provide several different types of CRT displays for the user's selection. Two basic types of graphic display options are provided. The first is the display of link performance information, which is cumulative in nature--namely, delay time, average speed, average occupancy, stops per vehicle, etc. Queue length displays that are instantaneous in nature can also be displayed. Note that both types of displays are generated in pseudo real time [additional information is provided in the report by Chin and Eiger (4)]. In addition, both performance and display types are under operator control; i.e., the operator can interrupt the program execution, alter either display or performance type, and resume program execution. In addition to

Figure 5. Operator commands and system responses.

```
SYSTEM
STARTUP

????
     LEVEL 1 SYSTEM STARTUP
     LEVEL 2 BYPASS SHUTDOWN FILE READ
???? EXECUTE REQUEST OR CANCEL ?
????

SPECIFY
TOD CONTROL

????
     LEVEL 1 SYSTEM CONTROL
     LEVEL 2 ACTIVATE
     LEVEL 3 TRAFFIC CONTROL
     LEVEL 4 SYSTEM
     LEVEL 5 TIME OF DAY
???? EXECUTE REQUEST OR CANCEL ?
????

SYSTEM STATUS
REQUEST

                  * * * TRAFFIC SYSTEM STATUS * * *

COMMUNICATIONS            CONTROLLERS             DETECTORS
    NORMAL                   NORMAL                 NORMAL


      ***  15 MINUTE STATUS AND PERFORMANCE REPORT ***  PAGE  1

           DATE APR  5 1981             TIME 0801

                CHANGES SINCE LAST REPORT

             TIME     TYPE    NUMBER      CHANGE
             0757     SYS          0       STRT
             0757     SYS          0       TOD

                    DESIRED    ACTUAL    PATTERN     CIC        FAILURES
SECT.     TIME       MODE       MODE       NO.      IN OP.    COMM  CONT  DET

  1        757       TOD        TOD         1         0         0     0     0


ACTIVATE
MAN MODE
Pattern #4

????
     LEVEL 1 SYSTEM CONTROL
     LEVEL 2 ACTIVATE
     LEVEL 3 TRAFFIC CONTROL
     LEVEL 4 SECTION
     LEVEL 5 DATA ENTRY
      SECTION NO.                              =   1
     LEVEL 6 MANUAL PATTERN
     LEVEL 7 DATA ENTRY
      PATTERN NO.                              =   4
???? EXECUTE REQUEST OR CANCEL ?
????

SYSTEM STATUS
REQUEST

???? SUN APR  5, 1981 TIME  8: 6      SYSTEM STATUS

                   DESIRED    ACTUAL    PATTERN     CIC        FAILURES
 SECT.     TIME      MODE      MODE       NO.      IN OP.    COMM  CONT  DET
   1        805      MAN       MAN         4         0         0     0     0

   15-MINUTE REPORT PRINT ON
   HISTORY TAPE NOT READY
   WEATHER CONDITIONS: NOT SPECIFIED
   SPECIAL EVENTS: NONE SCHEDULED
????

SPECIFY
TOD CONTROL

????
     LEVEL 1 SYSTEM CONTROL
     LEVEL 2 ACTIVATE
     LEVEL 3 TRAFFIC CONTROL
     LEVEL 4 SYSTEM
     LEVEL 5 TIME OF DAY
???? EXECUTE REQUEST OR CANCEL ?
????
```

```
SYSTEM STATUS
REQUEST

???? SUN APR  5, 1981 TIME  8:13      SYSTEM STATUS

                   DESIRED    ACTUAL    PATTERN     CIC        FAILURES
 SECT.     TIME      MODE      MODE       NO.      IN OP.    COMM  CONT  DET
   1        812      TOD       TOD         1         0         0     0     0

   15-MINUTE REPORT PRINT ON
   HISTORY TAPE NOT READY
   WEATHER CONDITIONS: NOT SPECIFIED
   SPECIAL EVENTS: NONE SCHEDULED
????

REQUEST
INTERSECTION
STATUS
#22

????
     LEVEL 1 STATUS DISPLAY CONTROL
     LEVEL 2 CRT 1
     LEVEL 3 INTERSECTION STATUS
     LEVEL 4 INTERSECTION
     LEVEL 5 DATA ENTRY
      INTERSECTION NO.                         =   22
???? EXECUTE REQUEST OR CANCEL ?
????

???? SUN APR  5, 1981 TIME  8:28  INTERSECTION STATUS      CONTROLLER NO.   22
  SECTION NO.     1   CYCLE(ENTRY) 100   SPLIT(ENTRY)   20   OFFSET(ENTRY)   13
  CIC STATUS    REL   CYCLE(ACT.)  100   SPLIT(ACT.)    20   OFFSET(ACT.)    13
  CONT. STAT.   CPS   MIN. A-PHASE  11   MIN. B-PHASE   19   MASTER SYNCH.    N
  A-PHASE(BG)    20   A-PHASE(ACT)  20   B-PHASE(ACT)   80   B-PHASE(BG)     80
 SUBPHASE DURATIONS
S12   20  L34   41  S34   39
                         ****  LINK DATA  ****
 LINK      CIC      LINK     OCCUP     VOLUME     SPEED     STOPS    AVG. DELAY
  NO.     PHASE     DIR.      PCT        VPH       MPH     VEH/CYC    SEC/VEH
   57                EB        11        715        27        15        202
   51      S3        NB        11        715        27         3          3
   65      S2        WB        11        715        27        15        202
   45                SB        11        715        27         3          3
????

ACTIVATE
CPS MODE
Cycle=60
Split=18
Offset=8

????
     LEVEL 1 SYSTEM CONTROL
     LEVEL 2 RELEASE
     LEVEL 3 CONTROLLER PARAMETER SET
     LEVEL 4 DATA ENTRY
      CONTROLLER NO.                           =   22
???? EXECUTE REQUEST OR CANCEL ?
????

REQUEST
INTERSECTION
STATUS

???? SUN APR  5, 1981 TIME  8:32  INTERSECTION STATUS      CONTROLLER NO.   22
  SECTION NO.     1   CYCLE(ENTRY)  60   SPLIT(ENTRY)   18   OFFSET(ENTRY)    8
  CIC STATUS    REL   CYCLE(ACT.)  100   SPLIT(ACT.)    20   OFFSET(ACT.)    13
  CONT. STAT.   CPS   MIN. A-PHASE  11   MIN. B-PHASE   19   MASTER SYNCH.    N
  A-PHASE(BG)    20   A-PHASE(ACT)  20   B-PHASE(ACT)   80   B-PHASE(BG)     80
 SUBPHASE DURATIONS
S12   20  L34   41  S34   39
                         ****  LINK DATA  ****
 LINK      CIC      LINK     OCCUP     VOLUME     SPEED     STOPS    AVG. DELAY
  NO.     PHASE     DIR.      PCT        VPH       MPH     VEH/CYC    SEC/VEH
   57                EB        11        718        27        18        223
   51      S3        NB        11        718        27         3          3
   65      S2        WB        11        718        27        18        223
   45                SB        11        718        27         3          3
????

REQUEST
INTERSECTION
STATUS

???? SUN APR  5, 1981 TIME  8:36  INTERSECTION STATUS      CONTROLLER NO.   22
  SECTION NO.     1   CYCLE(ENTRY)  60   SPLIT(ENTRY)   18   OFFSET(ENTRY)    8
  CIC STATUS    REL   CYCLE(ACT.)   60   SPLIT(ACT.)    18   OFFSET(ACT.)     8
  CONT. STAT.    CI   MIN. A-PHASE  11   MIN. B-PHASE   19   MASTER SYNCH.    N
  A-PHASE(BG)    11   A-PHASE(ACT)  11   B-PHASE(ACT)   49   B-PHASE(BG)     49
 SUBPHASE DURATIONS
S12   11  L34   20  S34   29
                         ****  LINK DATA  ****
 LINK      CIC      LINK     OCCUP     VOLUME     SPEED     STOPS    AVG. DELAY
  NO.     PHASE     DIR.      PCT        VPH       MPH     VEH/CYC    SEC/VEH
   57                EB        11        716        27        16        262
   51      S3        NB        11        716        27         3          3
   65      S2        WB        11        716        27        16        262
   45                SB        11        716        27         3          3
????
```

the graphic displays above, various alphanumeric displays are available, including system status, controller status, and intersection status. These displays are provided on the IBM 3277 screen. The system status display provides information on the current mode of operation of the system, broken down by section. The controller status display lists the current mode of operation of each controller in the signal system. Possible modes are on-line, off-line, critical intersection, or controller parameter set. The intersection status display provides the traffic signal timing and traffic flow parameters for a user-selected intersection.

Operator system control is achieved by operator commands selected from a display menu on the IBM 3277 screen. As discussed previously, various options are available. Note that the manual and controller parameter set options permit operator intervention in the automated control of the system; as a result, investigations concerning the possible impacts of manual intervention in automated control can be conducted. The operator's decision to preempt the automated control can be based on the surveillance information displayed on the CRT or any prior information that warrants such intervention. The sequence of operations for operator intervention is shown in Figure 4.

The operator control inputs are accomplished via the IBM 3277 keyboard as shown in the system configuration of Figure 3. The sequence of operator commands and system responses shown in Figure 5 illustrates the selection of several possible modes of control.

SUMMARY

The UTCS simulator described in this paper was developed to support current and future research in first-generation UTCSs. The simulator comprises a traffic simulation component (NETSIM/ICG) and a UTCS component. These components are interfaced through several routines that emulate the communication functions in a traffic control system. To test the UTCS simulator, a test network was coded. Hypothetical peak-period origin-destination volumes were assigned on the network. On the basis of the resulting link volumes, several traffic patterns were identified. For each traffic pattern identified, the TRANSYT signal optimization program (5) was used to find the optimal network signal timing plan. In all, eight histories and four timing plans were generated. The simulator was tested in all modes of control. The ratio of program run time to real time ranges from 1:50 to 1:10 depending on the size of the network, the number of vehicles in the network, and whether or not the graphic display options are used.

ACKNOWLEDGMENT

The development of the UTCS simulator was supported by a grant from the Office of University Research, Research and Special Programs Administration, U.S. Department of Transportation. The technical monitor for the project was Paul Ross of the Traffic Systems Division of the Office of Research, Federal Highway Administration.

REFERENCES

1. A. Eiger and S.M. Chin. The Development of UTCS/NETSIM/ICG: An Integrated Urban Traffic Control System-Network Simulation-Interactive Computer Graphics Program. U.S. Department of Transportation, Final Rept., Feb. 1982.
2. Traffic Network Analysis with NETSIM. FHWA, Implementation Package FHWA-IP-80-3, Jan. 1980.
3. Urban Traffic Control System First Generation FORTRAN IV Overlay Software (Extended Version). FHWA, Implementation Package FHWA-IP-79-4, May 1979.
4. S.M. Chin and A. Eiger. Network Simulation Interactive Computer Graphics Program. TRB, Transportation Research Record 835, 1982, pp. 52-66.
5. The TRANSYT Signal Timing Reference Book. FHWA, 1978.

Publication of this paper sponsored by Committee on Traffic Signal Systems.

Evaluation of a Bus Preemption Strategy by Use of Computer Simulation

DAVID A. BENEVELLI, A. ESSAM RADWAN, AND JAMIE W. HURLEY, JR.

The effects of implementing a bus preemption strategy on an arterial corridor (Monument Avenue) in Richmond, Virginia, were studied. The Urban Traffic Control System/Bus Priority System microscopic traffic simulation model was used to simulate the bus preemption system operation for various bus flow rates and bus stop locations. A benefit-cost analysis found bus preemption to be unjustified for the network. A comparison of benefit-cost ratios for the individual intersections showed a parabolic shape in the corridor. The benefits of bus preemption were found to be limited by the preemption algorithm structure and the bus stop location. A far-side bus stop was found to minimize the negative effects of bus preemption on automobile travel delay. The results were related to the control algorithm studied, and it was recommended that a more sophisticated control algorithm be developed for simulation studies and that similar studies be performed for other control algorithms.

Transportation system management (TSM) strategies have evolved because of the significant increase in travel demand in urban areas, the lack of additional land to expand the transportation system, and the increase in construction costs. These factors have led to the search for methods to improve the level of service of existing facilities with small investment costs. During the past several years, the need to reduce dependence on foreign petroleum imports has become an important fact of American life. The measure of effectiveness, passenger miles per gallon of fuel consumed, can be greatly improved through

TSM strategies that improve the use of transit systems. Bus priority treatments and particularly bus preemption strategies are possible means of improving transit service. These strategies reduce friction between buses and other vehicles in the traffic stream, delay due to traffic signals, and delay caused by the operating characteristics of the bus (acceleration and deceleration).

In general, bus preemption is the changing or maintaining of a traffic signal display in order to reduce the amount of stopped delay or, if possible, to prevent moving buses from stopping. The changing or maintaining of the signal status is referred to as red truncation or green extension. Red truncation refers to the situation in which a bus arrives at a signal that displays red and, because of the presence of the bus, a green display is given earlier than normal. Conversely, green extension refers to the situation in which a bus arrives at the signal just before the signal display turns red and the presence of the bus causes the green signal to be maintained until the bus passes through the intersection.

Bus preemption affects both the delay and fuel consumption of buses and automobiles. A bus aided by green extension will experience a reduction in travel time because it will not be required to wait through a red phase and it will save fuel because it will not experience either the speed-change cycle or the idling time associated with a stop. These benefits are also experienced by passenger cars that travel through the intersection during the green extension. However, the cross-street traffic will incur disbenefits of increased delay (the green-extension time) and fuel consumption. Similar impacts can also be observed for the red-truncation strategy.

The principal goal of this paper is to evaluate traffic performance in a network under the control of a specific bus preemption signalization strategy and to assess such a TSM strategy. To achieve this goal, the following objectives were identified:

1. Evaluate traffic performance under existing demands and operational conditions,
2. Evaluate the system with the bus preemption signalization strategy under changes in bus flow rates and loadings, and
3. Investigate the effect of the design characteristics of the network on traffic performance.

PREVIOUS RESEARCH

The earliest known bus preemption experiment was conducted in August 1967 by Wilbur Smith and Associates and the Bureau of Traffic Research, Los Angeles Department of Traffic, under a study financed by the U.S. Department of Housing and Urban Development (1). Two intersections in Los Angeles were studied: Broadway and First and Broadway and Second. The signals were preempted to give priority to buses traveling on Broadway. In discussing this experiment, Evans and Skiles (2) indicated that traffic signal delay constituted 10-20 percent of the average bus trip time. They concluded that signal delay would be the easiest type of bus travel time delay to reduce.

In 1975, Levinson, Adams, and Hoey (3) suggested the following warrants for bus preemption:

1. Reduction in total person delay as a result of bus preemption;
2. During the peak hour, a minimum of 10-15 buses carrying 400-600 passengers;
3. A minimum daily volume of 100 buses; and
4. Reducing the cross-street green while still providing the necessary clearance time.

During the late 1970s, many papers were written evaluating bus preemption and various preemption control strategies that used simulation models. Wood (4) used the microscopic Bus Priority Assessment Simulation (BUSPAS) program to test two bus preemption control strategies. Wood tested an inhibit strategy and a compensation control strategy. The inhibit strategy did not permit a phase that lost green time due to preemption to be preempted in the following cycle; cycle lengths remained constant. Under the compensation strategy, the green time was increased by a predetermined value in the cycle following a preemption in order to compensate for the green time lost to a preemption. The study concluded that inhibiting cycles could reduce the delay caused to other traffic by preemption. If inhibition did not reduce the added delay sufficiently, then compensation could.

Another study was done at the Transport and Road Research Laboratory (TRRL) in England by Vincent, Cooper, and Wood (5). Their study examined five variations of preemption strategy: (a) green extension only; (b) green extension, red truncation, inhibit; (c) green extension, red truncation, compensation; (d) red truncation, inhibit; and (e) red truncation, compensation.

The experiment considered four cases of different volumes, saturation flow rates, and signal timings. Several bus detector placements were also investigated. The researchers reported that the effects of green extension and red truncation were approximately additive. For this reason, strategies B and C proved to be far superior to D and E in reducing the average delay per bus.

Lieberman, Muzyka, and Schneider (6) reported on a simulation study that used the SCOT model. This study evaluated a network in Minneapolis under a fixed-time signal timing plan generated by SIGOP-II to minimize person delay and under a bus preemption control strategy. The bus preemption control strategy could call for (a) green extension, (b) red truncation, (c) the signal to cycle rapidly to reinstate the normal green phase, or (d) the signal to cycle to reinstate the green phase after satisfying other phase duration minimums. Although both strategies reduced delay over the existing case, the bus preemption system reduced delay by 42.5 passenger-h/h more than the signal timing strategy.

ANALYSIS

To evaluate the performance of the bus preemption control strategy, a benefit-cost analysis was conducted on an arterial corridor (Monument Avenue) in Richmond, Virginia, for the morning and evening peak-hour traffic conditions. Monument Avenue is a major east-west arterial that connects the suburbs with the central business district (see Figure 1). The study area consists of a 1.3-mile segment of Monument Avenue between the intersections of Roseneath Road and Staples Mill Road (see Figure 2) with a bidirectional average daily traffic (ADT) of approximately 25 000 vehicles. There are 14 at-grade intersections along this section. Six of the intersections are controlled by a traffic signal, and the remainder have two-way stop sign control of the cross street as shown in Figure 2. East of the Hamilton Street intersection is an access ramp to southbound I-195 for eastbound Monument Avenue traffic.

Bus stops are generally located 20 ft upstream of each intersection, as shown in Figure 3. The two exceptions are the far-side stops for westbound buses at Hamilton Road and Chantilly Street. An average dwell time of 30 s was assumed for the analysis. The Greater Richmond Transit Company (GRTC) operates bus service for the Monument Avenue corridor. GRTC route 1 serves the corridor with 6 buses/h during the peaks for an average bus headway of 10 min.

The estimated investment cost to provide bus preemption in the corridor was $62 400 for an optical detection system. The cost estimate was based on phase selectors and detectors for six intersections at $6000/phase selector and 12 bus emitters at $1100/emitter. Maintenance costs were assumed to 10 percent of the capital cost. After an assumed service life of 15 years, the equipment terminal value was assumed to be zero.

Travel time delay and fuel consumption were used as measures of road user cost. These measures were derived for all bus and automobile traffic. Passenger travel time delay cost was estimated at $5.50/passenger-h, and fuel consumption costs were estimated at $1.50 and $1.30/gal for gasoline and diesel fuel, respectively. The estimates of travel time delay and fuel consumption were developed by using two computerized microscopic traffic flow simulation models: the Urban Traffic Control System-Bus Priority System (UTCS-BPS) model (7-9) and NETSIM (10).

The UTCS-BPS program simulates traffic flow by modeling the movement of an individual vehicle (automobile, truck, or bus) in a network of links (streets) and nodes (intersections). The velocity-time trajectories, location, status, and moving and delay time of each vehicle are stored in a vector and updated every second. The vehicles are gener-

Figure 1. Monument Avenue study area.

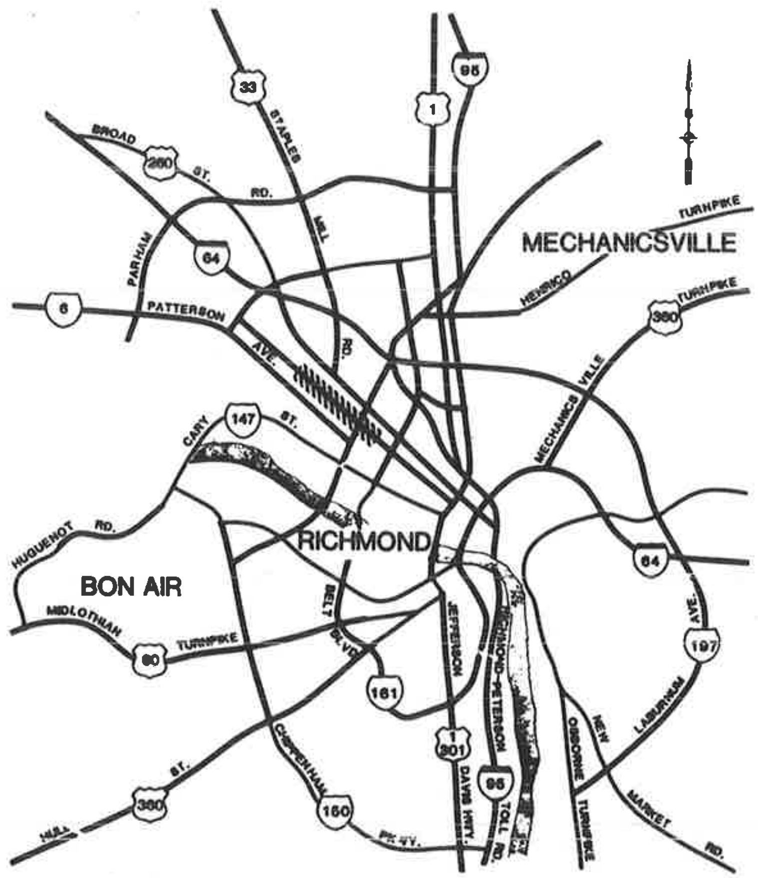


Figure 2. Monument Avenue corridor.

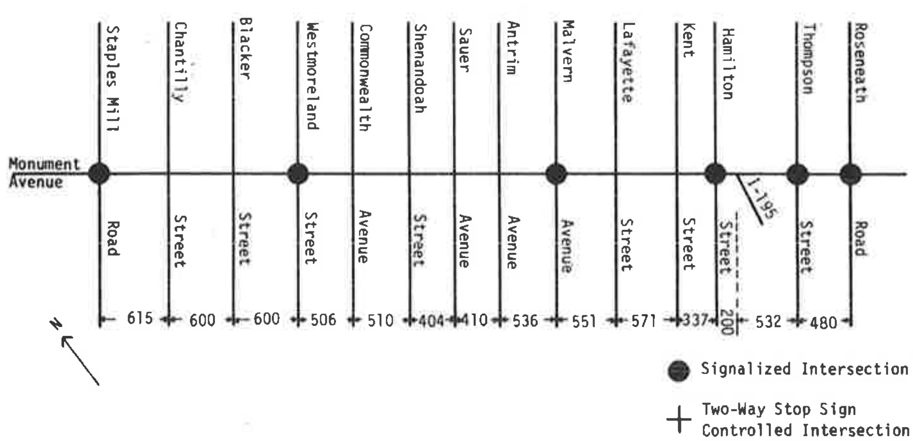


Figure 3. Link-node diagram of Monument Avenue corridor.

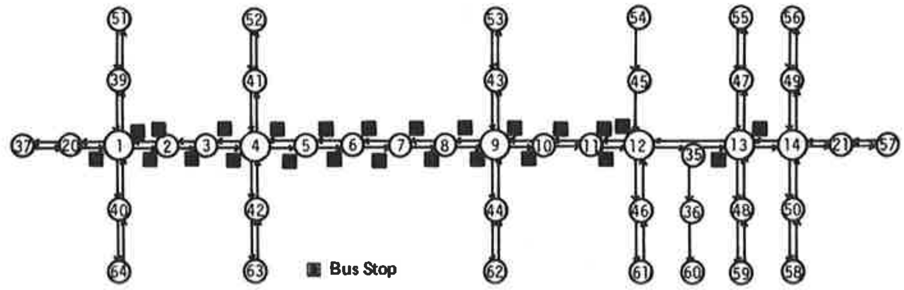
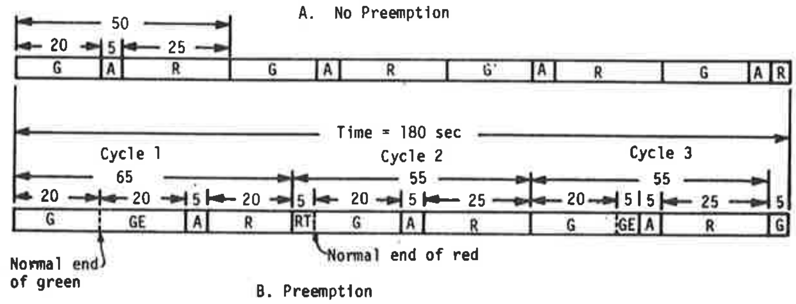


Figure 4. Effect of bus preemption on a two-phase signal.



G = Green
GE = Green Extension
A = Amber
R = Red
RT = Red Truncation

	Green + Amber Time	
Approach	No Preemption	Preemption
Main	100	110
Cross	80	70
Total	180	180

ated stochastically, and headways are assigned according to a shifted negative exponential function. The generated vehicles are assigned to an entry link and when conditions permit they are emitted onto the network links. Statistics are not collected for a vehicle until it occupies a network link. The bus and automobile travel time delays are included in the UTCS-BPS output. NETSIM read the velocity-time trajectories produced by UTCS-BPS and used a table look-up procedure to determine fuel consumption.

Five simulations were made of both the no-preemption case and the preemption case. The results for each case were averaged before inclusion in the benefit-cost model. Each simulation replicated 30 min of real time.

BUS PREEMPTION ALGORITHM

The UTCS-BPS model updates a node's signal status once every second. The approaches to a node are checked to determine the possibility of bus preemption only if certain conditions are met. For red truncation, these conditions are

1. The current phase has been active for a minimum period of time (20 s),
2. At this time the current phase is not being extended, and
3. A previously computed time for red truncation to occur at the node is less than or equal to the present time in simulation.

For green extension, the conditions are

1. A bus must be within the detector zones of the intersection or network and
2. A red truncation must not be scheduled to occur at the node at this time.

The algorithm is capable of granting signal preemption to any one of four approaches to an intersection. However, for the purpose of this study, buses were only simulated on the arterial.

The possible effects of bus preemption on a simple two-phase signal cycle are shown in Figure 4. The bar charts indicate the signal aspect for a bus preemption instrumented intersection approach. Case A shows the normal repetition of a 50-s cycle with 50-50 splits for a pretimed controller. Case B indicates how the signal cycle can be altered by the granting of a green extension, a red truncation, and another green extension to buses on the approach.

It is clear from the bar graphs that a green extension has greater potential to reduce bus signal delay than a red truncation. A green extension can reduce delay by the length of the preceding red period whereas a red truncation can only save the normal red phase time minus the minimum phase duration.

BENEFIT-COST MODEL

Because the two alternatives examined in this study are mutually exclusive, an incremental benefit-cost analysis model is used. The relation is given by

$$B/C = [-(U_p - U_B) - (K_p - K_B)] / [-(I_p - I_B)(CR_{i,n}) + (T_p - T_B)(SF_{i,n})] \quad (1)$$

where

B/C = benefit-cost ratio (on an equivalent uniform annual basis);
U_p = annual user cost for the preemption case;
U_B = annual user cost for the "do-nothing" case (base case);
K_p, K_B = annual maintenance and operations cost for the preemption and the base case, respectively;
I_p, I_B = investment cost for the preemption and the base case, respectively;

$CR_{i,n}$ = capital recovery factor for vest charge rate i and analysis period n (years), given by

$$CR_{i,n} = i(1+i)^n/[(1+i)^n - 1] \quad (2)$$

T_P, T_B = terminal value of the equipment for the preemption and the base case, respectively; and

$SF_{i,n}$ = sinking fund factor for vest charge rate i and analysis period n (years), given by

$$SF_{i,n} = (i)/[(1+i)^n - 1] \quad (3)$$

Given the previously stated assumptions, Equation 1 reduces to

$$B/C = [-(U_p - U_B) - K_p]/(-I_p\, CR_{i,n}) \quad (4)$$

SIGNAL TIMING

A signal timing plan was generated for the Monument Avenue network in order to minimize vehicle delay in the no-preemption case. The timing plan was developed for the morning and evening peak hours by using the Signal Operations Analysis Package (SOAP) (11) and the Traffic Network Study Tool (TRANSYT) (12). Each of the signalized intersections was modeled by SOAP to determine the phasing pattern and cycle length required to minimize vehicle delay and excess fuel consumption. The SOAP analysis also determined optimal cycle length for the individual intersections. The signal phasing chosen for the morning simulation was two-phased at all intersections except for Staples Mill Road, which had an exclusive left-turn phase on Monument Avenue. For the evening simulation, a two-phase operation was selected for the Roseneath, Thompson, and Malvern intersections, a three-phase operation for Hamilton and Staples Mill, and a four-phase sequence for Westmoreland. At all intersections the cross-street traffic was served by a single phase.

The TRANSYT model was then used to simulate traffic in the network macroscopically by using the phasing pattern results from SOAP. A range of cycle lengths were tested to determine the one that minimized a performance index (PI). The PI was a function of vehicle delay and the number of vehicle stops made. The range of cycle lengths tested was based on the results of the SOAP analyses. The results of the TRANSYT analyses are given below (X = cycle length not tested):

	Performance Index	
Cycle Length (s)	Morning	Evening
45	43.43	X
50	39.18	X
55	40.15	X
60	41.07	112.75
65	41.88	X
70	42.75	X
75	43.79	88.93
80	45.83	X
85	48.12	84.24
90	X	86.71
95	X	87.73
100	X	88.00
105	X	89.83
110	X	91.90
120	X	95.75

The cycle length, offsets, and splits generated by the TRANSYT program for the morning and evening peak hours, which minimized the PI, were used in the UTCS-BPS simulations. The morning cycle length was 50 s, and the evening peak hour used an 85-s cycle length.

The offsets were maintained throughout the no-preemption case simulations. However, the traffic signal control algorithm in UTCS-BPS could not maintain or reestablish the proper offset after a cycle at an intersection had been preempted.

ANALYSIS RESULTS

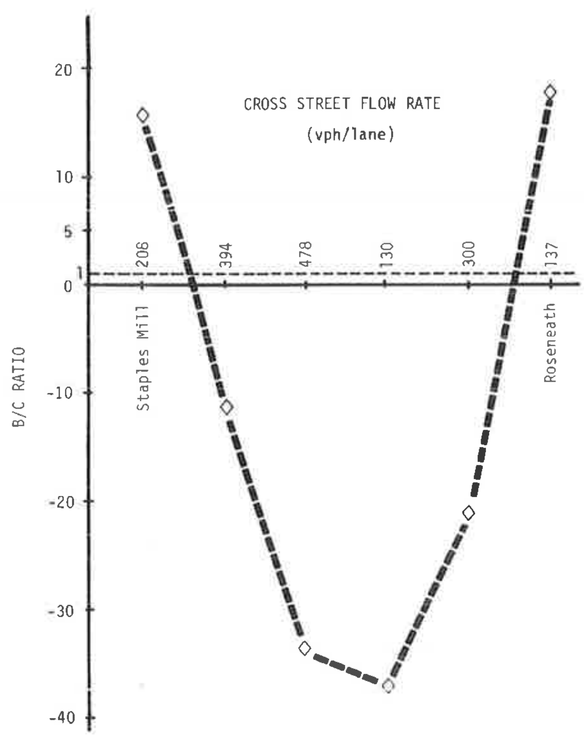
Both the morning and evening peak-hour analyses resulted in negative benefit-cost ratios for the network, which indicated that bus preemption caused higher road user costs than no preemption. A value of -12.042 was computed for the morning analysis and -15.399 for the evening. To determine possible causes for the negative benefit-cost ratios, the morning peak-period data were analyzed on an intersection-by-intersection basis.

The individual intersection benefit-cost ratios calculated from the morning simulation results are shown in Figure 5. The results were plotted according to the location of the intersection irrespective of cross-street automobile flow rates. The higher of the two opposing cross-street automobile flow rates at each intersection is shown in the figure.

A parabolic shape is apparent from the plot in Figure 5. A statistical analysis showed that the road user cost measures over the total network were not significantly different for the no-preemption and preemption cases at the 95 percent confidence level. However, the analysis showed that automobile delay was significantly different for the no-preemption and preemption cases at the three intersections with the lowest benefit-cost ratios.

The bus preemption control algorithm was reviewed as a possible cause of the negative benefit-cost ratio. The logical structure of the program grants priority to red truncation over green extension. Because the green extension form of preemption can provide greater benefits to buses than red truncation, the algorithm structure limits the benefits of bus preemption.

Figure 5. Benefit-cost ratio versus cross-street flow rate: morning peak period.



The review also indicated that the multiple phasing and the short cycle lengths combined minimize the benefits of preemption to buses. The short cycle lengths meant that the phase lengths were shorter. When preemption consisted of green extension, the current green phase length could be doubled in duration. But extending a 20-s phase another 20 s does not provide the added passage time that doubling a 40-s phase does. The extra passage time from a longer cycle length would greatly assist a bus in peak-hour traffic. For the red truncation form of bus preemption, a minimum phase duration of 20 s was required before the red signal display could be truncated. For example, if a bus were stopped by a red phase with a normal duration of 25 s, the maximum possible benefit to the bus if red truncation were granted would be 5 s. Obviously, with longer phase durations the possible benefits to bus passengers would be greater.

The inability of the algorithm to reestablish offsets once a signal preemption occurred may also have adversely affected road user costs. A platoon of vehicles traveling down the arterial receives important travel time benefits due to signal coordination in the no-preemption case. However, when a signal preemption occurs the signals are no longer coordinated and an approaching platoon of vehicles may experience excessive delays, depending on when they arrive at the uncoordinated signal. As more signals on the arterial are preempted, the benefits of any adjacent coordinated signals disappear and vehicle delay increases.

Another factor that may have affected the ability of the bus preemption system to perform well enough to generate a positive benefit-cost ratio was the bus stop location. All of the stops were near-side stops except two, of which only one was at a signalized intersection. While boarding and alighting passengers at a near-side stop within an approach detection zone, a bus would cause red truncations and green extensions of the signal. These preemptions occurred even though the bus was not ready to depart the stop and reenter traffic. These preemptions caused delay to cross-street automobiles while the bus did not experience any reduction in travel time delay.

The problem is not with the control algorithm alone. This is an actual problem encountered with the bus preemption hardware. One report (13) recommends that, in installing the bus preemption optical detection system, all bus stops be moved to far-side locations, if practical. The report estimates the cost of moving a bus stop in New Orleans at approximately $5500. The cost depends on the quality of the facilities at the stop, such as a shelter or the amount of signing. The cost of providing new locations or moving stops could be prohibitive. It was therefore decided to analyze higher bus flow rates over the Richmond network and to compare the results with those obtained from simulations with the bus stops outside the detection zones. Bus flow rates of 15 and 25 buses/h were studied along with the 6-buses/h flow rate.

One simulation run was made for the no-preemption case. Five runs were made of the preemption case and the results were averaged. The evening peak-period conditions were adopted, and comparisons were made of the changes (no-preemption delay minus preemption delay) in automobile travel time delay and bus travel time delay. Figure 6 shows these comparisons. Line a indicates where automobile passenger delay increases (disbenefits) between no preemption and preemption are equally offset by bus passenger delay reductions (benefits) at an automobile occupancy rate of 1.4 passengers/automobile and a bus occupancy rate of 35 passengers/bus. Data points in the area below and to the left of the line indicate that total passenger travel time delay increases from the no-preemption to the preemption case. Points above and to the right of the line indicate a decrease in total passenger travel time delay.

Only one case showed a decrease in total passenger delay. This was the 25-buses/h main street bus flow rate with bus stops located at midblock. The worst case was also the 25-buses/h flow rate, but the bus stops were located at the near side of the intersection. It was decided to review the control algorithm and its operation with multiple-phase signals again.

Multiple phases minimized the benefits of preemption under the control algorithm. Extra phases meant shorter phase durations and therefore shorter green extension or red truncation periods. The control algorithm also did not have the capability to skip phases. This meant that a bus, arriving during a red period and eligible for red truncation at a signal with a four-phase sequence, would have to truncate the three remaining phases before being served by the early call to the normal green phase for its approach.

To assess the impact on bus preemption of two-phase signals with different bus stop locations, another series of simulations was performed. Bus flow rate and bus stop location were varied under a two-phase signal operation while the same cycle length as the original evening peak-period signal timing plan was maintained. Again, one 30-min simulation was done of the no-preemption case while the average of five preemption case simulations was used to determine the changes in passenger car and bus travel time delays. Figures 7 and 8 show the results.

Figure 6. Effect of bus stop location on changes in delay: multiphase signal operation.

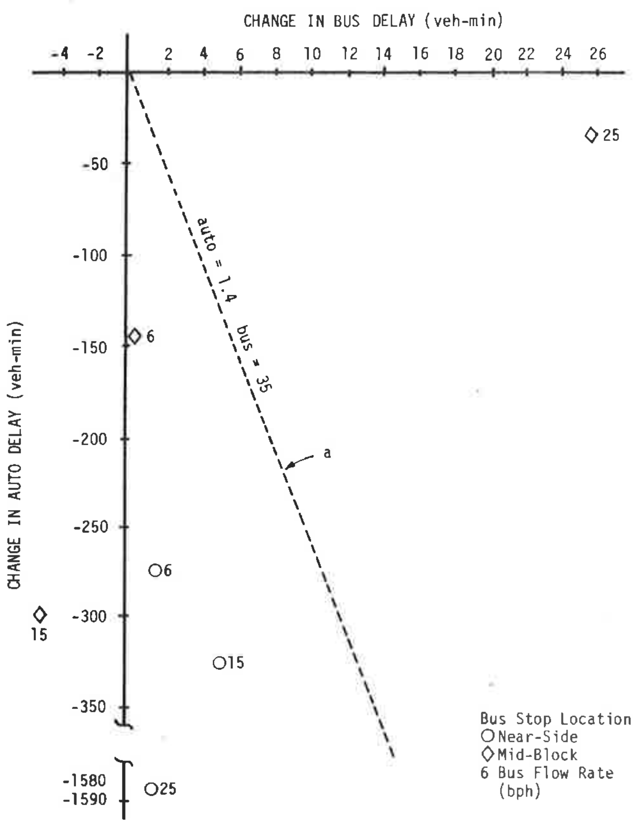


Figure 7. Effect of bus flow rate on changes in delay: two-phase signal operation.

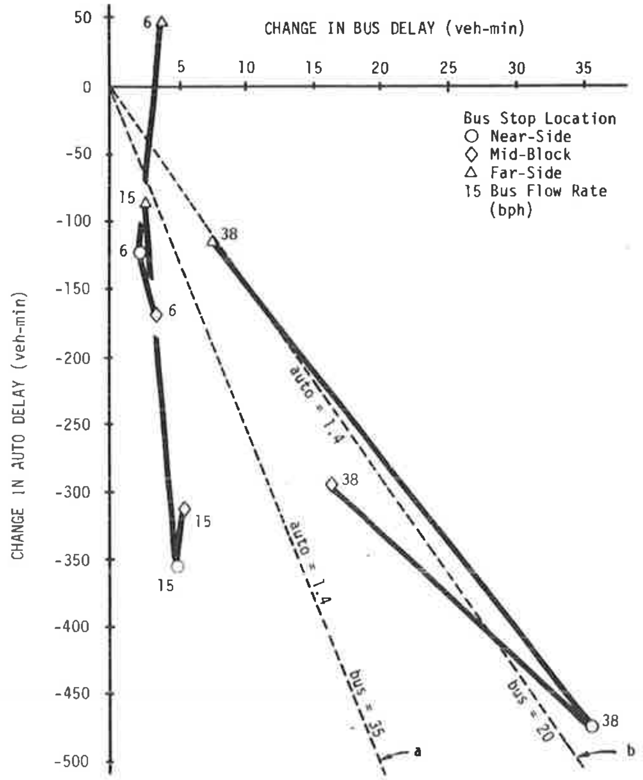


Figure 8. Effect of bus stop location on changes in delay: two-phase signal operation.

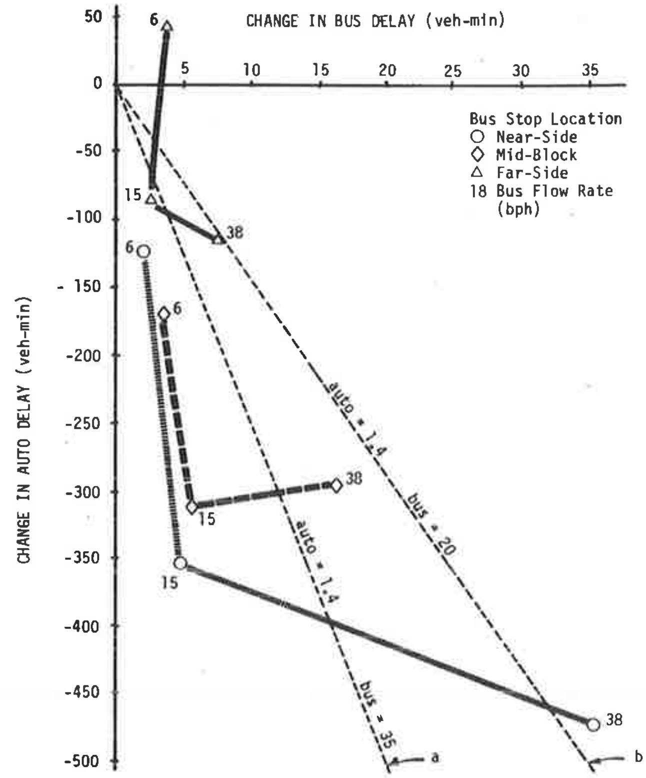


Figure 7 shows the results plotted with a constant bus flow rate and varying bus stop location. A comprehensible pattern does not emerge from the results. Lines a and b represent the points at which the changes in bus and automobile passenger travel time delays are equal for the occupancy rates shown. The 38-buses/h main street bus flow rate indicates that bus preemption can decrease total passenger delay if bus loads exceed 35 passengers. In general, if the bus passenger load drops to 20 passengers, bus preemption increases total passenger delay. The 6-buses/h flow rate with a far-side stop location decreases total passenger delay under either loading, whereas the far-side stop with a 15-buses/h flow rate appears to increase total passenger delay slightly.

Figure 8 shows the results plotted with a constant bus stop location and varying bus flow rate. A more definitive pattern becomes visible. As expected, the near-side stop location has the most negative impact on the change in passenger car delay. The far-side stop has the least impact. These results indicate that the far-side bus stop may have the best possibility, of the three stop locations, of providing a benefit-cost ratio greater than one under the bus preemption control algorithm and a two-phase signal. This finding supports previous findings that recommend far-side bus stop locations for use with bus preemption systems (13). This does not mean that preemption cannot be effectively accomplished with near-side or midblock stop locations. The findings only indicate that preemption can reduce total passenger delay more readily with far-side bus stop locations than with near-side stop locations.

CONCLUSIONS AND RECOMMENDATIONS

The analysis of the Richmond network indicated that bus preemption was not cost effective. The analyses revealed that the near-side bus stop locations and multiple signal phasing combined to reduce the benefits of preemption. The problems associated with bus stop location and multiple signal phasing were related to the bus preemption control algorithm. The algorithm was not sophisticated enough to simulate the signal system operations that are possible with technology available today. The results may vary under other control algorithms.

During the performance of this research, several items of concern have been noted regarding the data and methodologies used. The following recommendations are offered for further consideration:

1. Microscopic traffic simulation programs should be programmed to simulate several types of bus preemption control strategies. The preemption control algorithms should be sufficiently sophisticated to (a) simulate bus preemption at fully actuated traffic signals, (b) simulate bus preemption under a coordinated signal system in which coordination of the signals is reestablished after a bus preemption by phase skipping or smoothing of the signal cycle length, and (c) allow phase skipping when a bus preemption call is made.

2. A similar research effort should be performed for other control algorithms to determine how the algorithm affects the cost-effectiveness of bus preemption.

3. An investigation should be performed to determine whether or not automobiles tend to platoon around buses where bus preemption systems exist. An interior network intersection was simulated as an isolated intersection under the same traffic conditions. Bus preemption provided more user benefits under the isolated scenario than under the network scenario for the intersection. This may indicate

that vehicle platoons may be adversely affected by preemption in a network under this control algorithm.

ACKNOWLEDGMENT

We wish to express appreciation to the National Science Foundation and Virgina Polytechnic Institute and State University for their financial support of this research. We also wish to express our appreciation to Robert L. Anderson and Ralph H. Rhudy of the Richmond Traffic Engineering Department for their assistance in obtaining the traffic data for this research.

REFERENCES

1. Westinghouse Air Brake Co.; Melpar, Inc.; Wilbur Smith and Associates; and Institute of Public Administration. Study of Evolutionary Urban Transportation: Volumes I, II, and III. U.S. Department of Housing and Urban Development, Feb. 1968.
2. H.K. Evans and G.W. Skiles. Improving Public Transit Through Bus Preemption of Traffic Signals. Traffic Quarterly, Vol. 24, No. 4, Oct. 1970.
3. H.S. Levinson, C.L. Adams, and W.F. Hoey. Bus Use of Highways: Planning and Design Guidelines. NCHRP, Rept. 155, 1975.
4. K. Wood. Bus-Actuated Signal Control at Isolated Intersections: A Simulation Model. Transport and Road Research Laboratory, Crowthorne, Berkshire, England, Supplementary Rept. 373, 1978.
5. R.A. Vincent, B.R. Cooper, and K. Wood. Bus Actuated Signal Control at Isolated Intersections: Simulation Studies of Bus Priority. Transport and Road Research Laboratory, Crowthorne, Berkshire, England, Rept. 814, 1978.
6. E.B. Lieberman, A. Muzyka, and D. Schneider. Bus Priority Signal Control: Simulation Analysis of Two Strategies. TRB, Transportation Research Record 663, 1978, pp. 26-28.
7. Peat, Marwick, Mitchell and Company; General Applied Science Laboratories. Network Flow Simulation for Urban Traffic Control System: Appendix I Program Manual. FHWA, 1971.
8. G. Radelat. Bus Priority Systems Supplement to the Subroutine Documentation of the MITRE'S Version of the Original UTCS-1 Model. Traffic Systems Division, Office of Research, FHWA, 1973.
9. G. Radelat. A Bus Preemption Algorithm and Its Test by Simulation. Traffic Systems Division, Office of Research, FHWA, 1973.
10. NETSIM Model: Volumes 1-5. FHWA, 1977.
11. Signal Operations Analysis Package. Offices of Research and Development, FHWA, Implementation Package 79-9, July 1979.
12. The TRANSYT Signal Timing Reference Book. FHWA, 1978.
13. JHK and Associates. Traffic Signal Preemption for Buses. Office of Transit Administration, City of New Orleans, Oct. 1980.

Publication of this paper sponsored by Committee on Traffic Signal Systems.

Heuristic Programming Approach to Arterial Signal Timing

RAMEY O. ROGNESS AND CARROLL J. MESSER

A heuristic programming approach to minimum-delay arterial street signal timing plan optimization is presented. The selection of a good heuristic solution for phasing sequence, cycle length, and green splits is demonstrated. The approach demonstrates a procedure for use by the traffic engineer in selecting the phase sequence, cycle length, and offsets for an arterial street for developing a minimum-delay signal timing plan from existing computer programs. The heuristic procedure is to use the PASSER II computer program for maximum bandwidth progression optimization to select the phasing sequence and the initial starting point for use in the TRANSYT 6 computer program to develop a minimum-delay performance index solution. This permits all signal timing variables to be optimized. Comparisons are made between this heuristic solution and the best signal timing plan developed (considering all possible combinations a priori) by the TRANSYT program. An evaluation of use of the PASSER II green split routine versus the TRANSYT STAR1 routine on the program solution was performed. The heuristic procedure, when restricted to the minimum-delay cycle length, resulted in at least a good solution versus a TRANSYT best solution that used a measure index. A comparison of the PASSER II green splits and the TRANSYT STAR1 routine produced mixed results.

The primary emphasis of this paper is on fixed-time, common-cycle, coordinated traffic signals with multiple-phase control for arterial streets. A heuristic programming approach to minimum-delay optimization of signal timing for arterial streets is presented. The area of application is a linear system of high-type signalized intersections.

Improving the effectiveness of traffic-control variables has been thought to contribute to reducing congestion and relieving those conditions that impede the flow of traffic. Selection of a signal timing plan is complicated by the large number of available alternatives and the interrelations among the signal timing variables (1). Considerable research has been done on the coordination of traffic signals on arterial streets (2). Efforts have been directed toward computerized signal timing optimization procedures, strategies, and techniques that would provide for signal timing plans superior to those in use. Improvements in operational efficiency and safety have been consistent long-term goals.

Despite the various methods available to determine arterial signal settings, a maximum bandwidth progression solution has historically been the approach preferred by traffic engineers (3-5). This arises in part from the lack of computational complexity in use and the ability to visualize the goodness of the results.

Although progression has been widely accepted and used, questions have arisen concerning whether it provides a good arterial solution at the expense of the cross-street traffic. Other methods for coordinating signals have been proposed in which the objective of optimizing is an index of performance, such as delays or stops (6). Minimums for stops and delay do not necessarily coincide (7,8), although they can be close (9). The shift between the two regarding which is optimal for function minimization depends both on the degree of saturation and the stop penalty (10, p. 280).

The progression concept of minimizing the number of stops and increasing the number of through vehicles not forced to stop can be seen to be counter to the general philosophy of minimum delay. Maximum bandwidth does not necessarily mean minimum delays or stops for main-street traffic (11). Miller (12) was of the opinion that progression was best for low and moderate flow levels. Gordon (13) thought progression should only be used for low-volume levels. Ramon (14) thought that for low saturation maximum bandwidth was effective, that its effectiveness decreased with increasing saturation, and that, at moderate and high saturation, optimization of delays and stops should be used. Bayley and Tarnoff (15, 16) stated the familiar rule-of-thumb that up to 0.5-mile uniform signal spacing is ideal for progression. Gartner (17) contended that the conventional procedure should be to provide the best possible progression to accommodate heavy flow. Huddart (18) asserted that it was possible to arrive at a compromise between the two methods of computing traffic signal progression--i.e., maximizing bandwidth and minimizing delay (by using a stop penalty).

TRANSYT

The TRANSYT program has been widely used throughout Europe and the world and increasingly used in the United States (19,20). The program is classified as a macroscopic deterministic optimization procedure. It uses an objective function of weighted stops and delay for a performance index (PI) (21). TRANSYT is best suited for high-type intersections and control. The program optimizes phase durations and offsets. It was developed for application to dense signal networks with short spacings between intersections (less than 750 ft) (22).

The TRANSYT program is restricted in that it cannot optimize cycle length or oversaturated conditions. The computer program is limited by three features:

1. Because it is a nonlinear programming formulation with a gradient search technique, it cannot guarantee an optimal solution.
2. It cannot analyze loops directly. It uses a sequential flow solution approach that artificially severs loops.
3. It cannot analyze alternative phase sequences and cycle lengths for PI minimization.

This paper and the heuristic programming approach address the last of these three limitations.

PASSER II

The PASSER II computer program can be classified as a macroscopic deterministic optimization model. The arterial progression optimization section of the program can analyze the four possible arterial phase sequences per intersection and select from the phase sequences considered at each intersection the one that provides the best overall progression solution. The optimization procedure is an implicit enumeration of the minimum interference values performed by using a variant of the half-integer synchronization approach for relative offsets. The unique advantage of the PASSER II program over other optimization programs for signalization is that it can be used to consider and select multiple-phase sequences (23).

INTRODUCTION TO HEURISTIC PROCEDURE

The existing optimization algorithms for fixed-time signal timing plans all have a limitation in that the sequence (and number) of signal phases and the associated traffic movements must be specified. There is no optimization of phase sequences as part of the procedures of these programs.

The PASSER II optimization routine for arterial fixed-time signal plans is unique among the existing arterial and network signal timing optimization programs because it can determine the optimum phase sequence for each arterial intersection. Its limitation is that, because it is based on a variant of the maximum bandwidth progression solution, it might not optimally minimize vehicle delay.

To improve the computational efficiency of a computerized fixed-time minimum-delay signal timing plan optimization program, it would appear that the use of a maximum bandwidth program to select the multiple phase sequences would appear to be an effective method. To evaluate this approach, the heuristic procedure is to use the PASSER II multiple-phase sequence selection optimization routine in selecting each of the intersection phase sequences to be used in the TRANSYT6 program. The traffic signal settings obtained as optimal from the PASSER II program include phase sequence, phase interval duration, cycle length, and intersection offsets.

The TRANSYT program has an internal routine (STAR1) as a user option for determining phase interval durations, but it requires phase sequence, minimum green times, cycle length, and intersection offsets as input data. A case study was designed to demonstrate the heuristic by using a single arterial street. This case study approach does not permit generalization of the results but demonstrates the approach and use of the process for a real-world problem.

CASE STUDY EVALUATION AND VALIDATION

Introduction

The research conducted was intended primarily to evaluate whether the PASSER II multiple-phase sequence selection optimization, used as the phase sequence input to the TRANSYT6 program, resulted in a good solution from the TRANSYT program. Second, an evaluation was made as to whether using an optimized signal timing plan from the PASSER II program as the initial starting point for the TRANSYT program gave a better solution than using the TRANSYT STAR1 procedure. Because TRANSYT and the other network signal timing optimization programs in use can only guarantee a local optimum, this can be an important consideration in finding a better solution.

Signal Timing Comparisons

An investigation was conducted to determine which of the signal timing plans corresponded to the TRANSYT optimal solution. Total enumeration permitted the selection of the optimal TRANSYT solution for the conditions modeled. This investigation also considered the possibility of the PASSER II and TRANSYT optimal solutions being the same and whether the PASSER II optimal cycle length was the same as the TRANSYT optimal cycle length (24). The signal timing results have been reported elsewhere (25).

Model Arterial

A four-signal arterial street was selected for the evaluation. It was thought to be large enough that

Figure 1. Skillman Avenue line drawing showing intersection spacing.

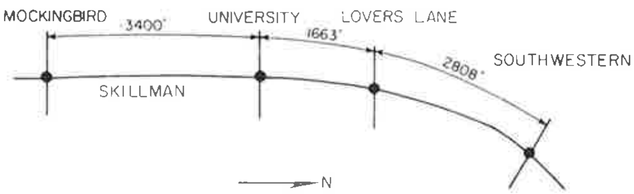
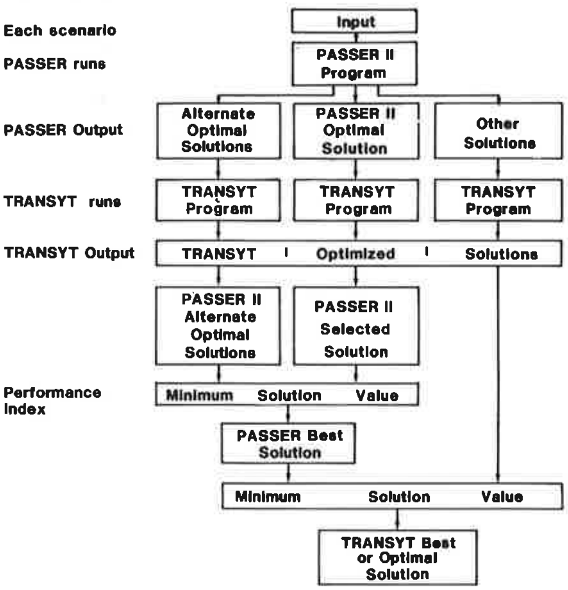


Table 1. Comparison of PASSER II and TRANSYT optimal solutions for three spacing scenarios.

	PASSER II		TRANSYT	
Spacing Scenario	Cycle Length (s)	Phasing Arrangement[a]	Cycle Length (s)	Phasing Arrangement[a]
Full-scale	100	3-4-3-4	80	1-2-3-1
Half-scale	90	4-4-4-3	80	1-2-4-2
Quarter-scale	80	4-3-3-4	80	2-4-3-2

[a] 1 - left turns first, 2 - through movements first, 3 - leading green, 4 - lagging green.

Figure 2. Flowchart of PASSER II and TRANSYT solutions.



signal and link characteristics would not especially affect traffic behavior and the results of the study.

It was decided to evaluate three cycle lengths for minimum-delay and progression solution interaction. The three cycle lengths selected were 80, 90, and 100 s, which appeared to be representative values and still provided a nominal range and three solution points.

To permit some range of spacing to be considered, three intersection spacings--full-scale, half-scale, and quarter-scale--were used to study the effect of the interrelations between cycle length and intersection spacings. This also permitted program biases to be considered. The TRANSYT program (from its platoon dispersion model) is considered to be applicable to short signal spacing (less than 750 ft), whereas the progression (PASSER II) programs are more dependent on the concept of ideal spacing (space periodicity) of about 0.25 to 0.5 mile. The three spacing scenarios permitted consideration of a long spacing (almost too long for progressive movement), a moderate spacing (which might be considered suitable for progression), and a short spacing (which might be considered suitable for TRANSYT).

The arterial street selected, Skillman Avenue, was not considered ideal for either progression or minimum-delay objectives. In general, the four intersections are high-type and all signalization is multiple-phase with protected turning. Figure 1 shows the full-scale intersection spacing. The three intersection spacings considered were as follows:

	Link Spacing (ft)		
Link	Full-Scale	Half-Scale	Quarter-Scale
South of Mockingbird	3000	3000	3000
Mockingbird to University	3400	1700	850
University to Lovers Lane	1663	832	416
Lovers Lane to Southwestern	2808	1404	702
North of Southwestern	3000	3000	3000
Cross street approaches	2000	2000	2000
Entry links	1000	1000	1000

Fixed speeds were used for all PASSER II runs. The existing arterial characteristics, cycle lengths, and volumes were used to determine a PASSER II optimized speed solution; those speeds were then fixed for all runs.

COMPARISON OF SOLUTIONS

The following program run combinations were considered for the study:

1. Cycle lengths--80, 90, and 100 s;
2. Intersection spacings--full-scale, half-scale, and quarter-scale; and
3. Splits--STAR1 and PASSER II.

For each of the combinations, a separate run was made for each program. The PASSER II optimal solution and the TRANSYT solution for each run were compared.

The optimal solutions for the PASSER II runs and the TRANSYT runs for the three scenarios are given in Table 1. Because the TRANSYT program is a heuristic, its final solution may depend on the initial starting point. There is no way to determine a priori the best solution that can be obtained. To determine the best TRANSYT solution, it was necessary to carry out a complete, total, and explicit classical nonlinear programming enumeration of all the combinations. This allowed the various solutions to be compared.

Each of the solutions was separately provided a descriptor. The PASSER II optimal solution that was obtained from the PASSER II program was termed the selected PASSER II solution. The alternative optimal PASSER II solution that was the lowest TRANSYT solution was termed the PASSER best solution. The TRANSYT best, or optimal, solution was the solution from the TRANSYT program that had the lowest PI. Figure 2 shows a flowchart that describes the solutions.

PASSER II and TRANSYT6

The comparison of cycle lengths for the TRANSYT and PASSER II optimal results (Table 1) would indicate, for this study, that the PASSER II optimal cycle length is not usually the minimum-delay cycle length. The PASSER II and TRANSYT cycle lengths selected as optimal were not necessarily the same. The PI shows the same trend:

	PI	
Spacing Scenario	Optimal PASSER II	Minimum PASSER II
Full-scale	91.26	85.71
Half-scale	81.56	79.60
Quarter-scale	76.44	76.44

For the full-scale scenario, the PI for the PASSER II solution (for minimum-delay input, 100 s) is 91.26 versus 85.71 for the 80-s cycle-length solution for TRANSYT. The half-scale scenario results are similar: the PASSER II solution (90 s) has a PI of 81.56 versus 79.60 for the 80-s cycle-length solution. There is no difference in solution for the quarter-scale scenario; both the progression and minimum-delay optimal cycle lengths are the same (80 s).

Comparison Measures

Because the PASSER II optimal solution did not match the TRANSYT minimum-delay solution, a measure of goodness of the PASSER II selected settings for a minimum-delay solution was needed. With the PASSER II optimized settings being used for all the phasing combinations, the absolute differences in the TRANSYT performance index for the optimal solution and the PASSER II setting should not differ greatly.

Indirect measures selected for weighting the goodness of a solution were rank and range. They provided a measure of difference and dispersion. The range measure was the percentage difference where the solution fell between the optimal and worst-case difference of PI. Although the range provided a measure of closeness, it could overstate the relative difference for a small range of PI. The second measure was to rank the solutions from lowest to highest PI. The four intersections resulted in 256 different phasing alternatives. The percentage rank was also used as a measure (rank over 256) along with the absolute rank.

Criteria were established by using these measures to determine subjectively the goodness of the PASSER II selected solution. It was believed that less than a 5 percent range or rank would indicate an excellent solution in comparison with the optimal. A range or rank difference of less than 10 percent was considered to be a good solution. A fair solution was a range or rank difference of 25 percent or less. A poor solution was a range or rank difference of 50 percent or less. A rank or range difference of greater than 50 percent was considered terrible. The criterion that was selected for the worthiness of the heuristic procedure was at least a good solution (by the rank measure). For each of the three spacing scenarios, the range and rank of the PASSER II selected phasing sequence and the best alternative optimal phasing sequence were used for the comparison.

Results for STAR1

The PI range and rank for the PASSER II selected and best solutions obtained by using the TRANSYT STAR1 green split were summarized by spacing scenario (see Table 2).

Full-Scale Spacing

Table 2 gives the range and rank for the PASSER II selected phasing sequence and the best alternative phasing sequence for the 80-s cycle length. The range percentage for both is 21, which would be fair. The rank for both is 19 (out of 256) or 7 percent, which would be considered good. The range and rank for the 90-s cycle length are also given in Table 2. The range for both the PASSER II selected and the alternative best is 30 percent, which corresponds to a poor solution for minimum delay. The corresponding rank and rank percentage for both are 56th and 22 percent, respectively, which is fair. For the 100-s cycle length, the PASSER II best solution has a range of 13 percent, a rank of 14, and a rank percentage of 6. This would correspond to a fair solution for range and a nearly excellent solution for rank.

The TRANSYT minimum-delay cycle length for the full-scale scenario is 80 s. The range and rank for

Table 2. Range and rank results of PASSER II solutions for three spacing scenarios.

Measure	80-s Cycle Best	80-s Cycle Selected	90-s Cycle Best	90-s Cycle Selected	100-s Cycle Best	100-s Cycle Selected
Full-Scale Scenario						
Phasing[a]	3-4-4-3	3-4-4-3	3-4-2-4	3-4-2-4	2-4-1-4	3-4-3-4
Range						
Percentage	21	21	30	30	13	41
Measure	Fair	Fair	Poor	Poor	Fair	Poor
Rank	19	19	56	56	14	141
Percentage	7	7	22	22	5	55
Measure	Good	Good	Fair	Fair	Excellent	Terrible
Half-Scale Scenario						
Phasing[a]	2-3-4-2	2-3-4-2	4-2-4-3	4-4-4-3	4-2-1-3	4-3-4-3
Range						
Percentage	1	1	9	20	19	38
Measure	Excellent	Excellent	Good	Fair	Fair	Poor
Rank	2	2	17	109	22	86
Percentage	1	1	7	42	9	34
Measure	Excellent	Excellent	Good	Poor	Good	Poor
Quarter-Scale Scenario						
Phasing	4-3-3-4	4-3-3-4	4-3-3-4	4-3-3-4	4-3-3-2	4-3-3-4
Range						
Percentage	22	22	30	30	43	49
Measure	Fair	Fair	Poor	Poor	Poor	Poor
Rank	15	15	96	96	162	181
Percentage	6	6	38	38	63	71
Measure	Good	Good	Poor	Poor	Terrible	Terrible

[a]See Table 1, footnote a.

the PASSER II best solution for 80 s are fair and good, respectively. The PASSER II best solution for 90 s had a range and rank that were poor and fair, respectively. For the 100-s cycle length, which was the best for progression, the PASSER II best solution has a fair range and a nearly excellent rank measure. The PASSER II best solution obtained by using the STAR1 procedure for the full-scale spacing scenario at the minimum-delay cycle length was good compared with the TRANSYT best solution achieved by using the rank measure as the basis of comparison.

Half-Scale Spacing

For the half-scale scenario (Table 2), the 80-s cycle length is considered first because it is the minimum-delay cycle length. The PASSER II selected solution and the best solution have a range percentage of 1, a rank of 2, and a rank percentage of 1. These correspond to an excellent solution.

The 90-s cycle length was the progression cycle length selected for the half-scale scenario. The results for the PASSER II best solution are 9 percent for range, a rank of 17, and a rank percentage of 7. These correspond to a good solution.

For the 100-s cycle length, the PASSER II best solution range is 19 percent, its rank is 22, and its rank percentage is 9. This would be considered a fair solution for range and a good solution for rank.

For the half-scale scenario at the minimum-delay cycle length, the PASSER II best solution provided an excellent minimum-delay solution. For the longer cycle lengths, the solutions provided were at least good by rank.

Quarter-Scale Spacing

For the quarter-scale scenario (Table 2), both the progression cycle length and minimum-delay cycle length were 80 s. The range for the PASSER II selected and best solutions is 22 percent, which is a fair solution. The rank for both is 15 and the rank percentage is 6, which shows a good solution.

The results for the 90- and 100-s cycle lengths, which are longer than optimal for both progression and minimum delay, show swift degradation. For the 90-s cycle length, the PASSER II best solution range is 30 percent. The rank is 96 and the rank percentage is 38. These measures provide a poor solution. The 100-s cycle length PASSER II best solution has a range of 43 percent. The rank is 162 and the rank percentage is 63, which would indicate a terrible solution.

At the minimum-delay cycle length, the PASSER II solution provided a good solution. However, for longer cycle lengths its solution results showed swift degradation, which is apparent in Table 3.

Results for SPLIT1

For each of the TRANSYT runs, a separate run was made in which the PASSER II green splits were used as the initial starting point. The PI range and rank for the PASSER II best solution were calculated from the optimal TRANSYT solution by using these SPLIT1 results (not the STAR1 results). Overall measures are given in Table 4. Range and rank results by spacing scenario are summarized in Table 5.

Full-Scale Spacing

The PASSER II split results for the full-scale spacing scenario show that, for the 80-s cycle length, the PASSER II best solution has a range of 17 percent, a rank of 10, and a rank percentage of 4. The range measures indicate a fair solution and the rank measures indicate an excellent solution.

The PASSER II best solution for the 90-s cycle length has a range of 9 percent, which indicates a good solution. Its rank is 3 and its rank percentage is 1, which indicates an excellent solution. The range is 31 percent for the 100-s cycle length (a poor solution). The PASSER II best solution rank

Table 3. Range and rank measures for START1 results for three spacing scenarios.

	80-s Cycle		90-s Cycle		100-s Cycle	
Spacing Scenario	Best	Selected	Best	Selected	Best	Selected
Range Measure						
Full-scale	Fair	Fair	Poor	Poor	Fair	Poor
Half-scale	Excellent	Excellent	Good	Fair	Fair	Poor
Quarter-scale	Fair	Fair	Poor	Poor	Poor	Poor
Rank Measure						
Full-scale	Good	Good	Fair	Fair	Excellent	Terrible
Half-scale	Excellent	Excellent	Good	Poor	Good	Poor
Quarter-scale	Good	Good	Poor	Poor	Terrible	Terrible

Table 4. Range and rank measures for SPLIT1 results for three spacing scenarios.

	80-s Cycle		90-s Cycle		100-s Cycle	
Spacing Scenario	Best	Selected	Best	Selected	Best	Selected
Range Measure						
Full-scale	Fair	Fair	Good	Good	Poor	Poor
Half-scale	Excellent	Excellent	Poor	Poor	Poor	Terrible
Quarter-scale	Fair	Fair	Fair	Fair	Poor	Poor
Rank Measure						
Full-scale	Excellent	Excellent	Excellent	Excellent	Fair	Fair
Half-scale	Excellent	Excellent	Poor	Terrible	Poor	Poor
Quarter-scale	Good	Good	Fair	Fair	Poor	Terrible

Table 5. Range and rank results for PASSER II SPLIT1 solutions for three spacing scenarios.

	80-s Cycle		90-s Cycle		100-s Cycle	
Measure	Best	Selected	Best	Selected	Best	Selected
Full-Scale Scenario						
Phasing	3-4-4-3	3-4-4-3	3-4-2-4	3-4-2-4	2-4-1-4	3-4-3-4
Range						
Percentage	17	17	9	9	32	32
Measure	Fair	Fair	Good	Good	Poor	Poor
Rank	10	10	3	3	37	37
Percentage	4	4	1	1	15	15
Measure	Excellent	Excellent	Excellent	Excellent	Fair	Fair
Half-Scale Scenario						
Phasing	2-3-4-2	2-3-4-2	4-2-4-3	4-4-4-3	4-2-1-3	4-3-4-3
Range						
Percentage	1	1	35	47	44	56
Measure	Excellent	Excellent	Poor	Poor	Poor	Terrible
Rank	4	4	119	161	68	85
Percentage	1	1	46	63	27	33
Measure	Excellent	Excellent	Poor	Terrible	Poor	Poor
Quarter-Scale Scenario						
Phasing	4-3-3-4	4-3-3-4	4-3-3-4	4-3-3-4	4-3-3-1	4-3-3-4
Range						
Percentage	23	23	20	20	33	35
Measure	Fair	Fair	Fair	Fair	Poor	Poor
Rank	19	19	64	64	125	137
Percentage	7	7	25	25	49	53
Measure	Good	Good	Fair	Fair	Poor	Terrible

is 37 and its rank percentage is 14, which corresponds to a fair solution.

For the PASSER II splits, the range and rank measures indicate excellent solutions for the 80- and 90-s cycle lengths. For the longer (100-s) cycle length the measures are marginal.

Half-Scale Spacing

For the half-scale scenario (Table 5), the PASSER II best solution has a range of 1 percent for the 80-s cycle length. The rank is 4 and the rank percentage is 1. These measures would classify the solution as excellent.

The measures for the 90-s cycle length solution show opposite results. The PASSER II best solution has a range of 34 percent (a poor solution). The rank is 119 and the rank percentage is 46, which gives a poor solution. The 100-s cycle length measures for the PASSER II best solution are similar. The range and rank percentage are 44 and 27, respectively. These measures classify the solution as poor.

For the PASSER II green splits, the measures show an excellent solution for the minimum-delay cycle length. Cycle lengths longer than the minimum-delay value cause severe degradation in the measures.

Quarter-Scale Spacing

For the quarter-scale scenario, the PASSER II best solution for the 80-s cycle length has a range of 22 percent. This corresponds to a fair solution. The rank is 19 and the rank percentage is 7, which would indicate a good solution.

The 90-s cycle length results show slightly higher measures for the PASSER II best solution. The range is 20 percent. The rank is 64 and the rank percentage is 25. These measures correspond to a fair solution.

For the 100-s cycle length, the results show a range of 32 percent, a rank of 125, and a rank percentage of 48. This would correspond to a poor solution. The quarter-scale scenario results show an increasing trend in the measures for cycle lengths longer than the minimum-delay cycle length.

Measures Summary

By using the classification scheme of a solution by the rank measure, the results for the STAR1 procedure can be summarized as follows:

Spacing Scenario	80-s Cycle	90-s Cycle	100-s Cycle
Full-scale	Good	Fair	Excellent
Half-scale	Excellent	Good	Fair
Quarter-scale	Good	Poor	Terrible

At the minimum-delay cycle length, the PASSER II best solution provides at least a good solution compared with the optimal solution. For the longer cycle lengths, the goodness of the optimal solution varies with individual cycle length and spacing. This comparison is with the results of each cycle length. The PI for the longer cycle length is higher than that for the 80-s cycle length. The results for the 80-s cycle length would indicate that the PASSER II best solution provides a good alternative to the optimal solution.

The classification results for the rank measure for the PASSER II green splits are summarized below:

Spacing Scenario	80-s Cycle	90-s Cycle	100-s Cycle
Full-scale	Excellent	Excellent	Fair
Half-scale	Excellent	Poor	Poor
Quarter-scale	Good	Fair	Poor

At the minimum-delay cycle length, the PASSER II best solution provides an excellent or good solution. The degradation in the rank measure for the longer cycle lengths is variable but pronounced.

It should be noted that, although the PASSER II green splits provided a good solution at the minimum-delay cycle length, the comparison was with the optimal solution for those green splits, not the best solution overall.

Table 6. PI for optimal solutions for three spacing scenarios.

Routine	Cycle Length (s)	PI TRANSYT	PI PASSER II Best Solution	PI PASSER II Selected Solution
Full-Scale Scenario				
SPLIT1	80	86.02	86.37	86.37
STAR1	80	85.30	85.71	85.71
SPLIT1	90	86.22	86.40	86.40
STAR1	90	85.98	86.46	86.46
SPLIT1	100	90.84	91.47	92.22
STAR1	100	90.64	90.82	91.26
Half-Scale Scenario				
SPLIT1	80	80.38	80.40	80.40
STAR1	80	79.57	79.60	79.60
SPLIT1	90	80.88	81.91	82.28
STAR1	90	80.92	81.15	81.56
SPLIT1	100	85.34	86.63	87.00
STAR1	100	85.50	85.87	86.23
Quarter-Scale Scenario				
SPLIT1	80	76.29	77.01	77.01
STAR1	80	75.71	76.44	76.44
SPLIT1	90	76.78	77.94	77.94
STAR1	90	76.82	78.02	78.02
SPLIT1	100	82.19	83.64	83.80
STAR1	100	81.91	83.37	83.54

STAR1 Versus SPLIT1

To compare the differences between the TRANSYT optimal solutions and the PASSER II best solutions for the STAR1 routine and the SPLIT1 routine, the PI values are used. This allows an absolute comparison (see Table 6).

Full-Scale Spacing

The PI values for the full-scale scenario for the PASSER II selected and PASSER II best solutions are the same for each split for the 80- and 90-s cycle lengths (Table 6). They are different for the 100-s cycle length. In a comparison of the results for SPLIT1 and STAR1 for the cycle lengths, the STAR1 PIs are lower. For this scenario, the internal TRANSYT green split routine, STAR1, gave a better (lower) PI.

Half-Scale Spacing

In the PI results for the half-scale scenario (Table 6), the PASSER II selected and best solutions are identical for the 80-s cycle length but different for the 90- and 100-s cycle lengths. The STAR1 routine provided lower performance values for the 80-s cycle length, and the PASSER II solutions provided lower performance values for the 90- and 100-s cycle lengths.

This is not the case for the TRANSYT best solution. For the 80-s cycle length, the STAR1 PI was much lower for the STAR1 splits than for the SPLIT1 procedure. However, for the 90- and 100-s cycle lengths, the SPLIT1 routine gave lower PIs than STAR1.

For the 90-s cycle length, the SPLIT1 performance index of 80.88 was slightly less than the STAR1 result of 80.92. The TRANSYT best PI of 85.34 from the SPLIT1 routine was again lower than the STAR1 value of 85.50. However, the PASSER solution results obtained by using the STAR1 routine were much lower.

Quarter-Scale Spacing

The quarter-scale scenario results summarized in Table 6 are different from results for the full-scale and half-scale scenarios. The 80-s cycle length results, in which the STAR1 PIs are lower than those for SPLIT1, are similar to the 80-s results for the full-scale and half-scale scenarios. For the 90-s cycle length, however, the SPLIT1 PIs for the TRANSYT best, PASSER II selected, and PASSER II best solutions are all lower than the values from the STAR1 routine. The results for the 100-s cycle length are reversed: the STAR1 procedure provides lower PIs than SPLIT1.

Summary of Splits

The results would indicate that under some conditions the PASSER II split routine provided better results than the TRANSYT internal STAR1 routine. It would appear that at the minimum-delay cycle length (80 s) the STAR1 routine was better than the PASSER II splits. The results for the other cycle lengths for the three scenarios, however, are mixed. In some instances, the PASSER II splits provided better results. In other instances, the PASSER II splits provided worse results.

This mixed behavior of the PASSER II split routine and the STAR1 routine would indicate that a revised PASSER II green split routine might improve its results. The STAR1 routine PI measures would indicate that it is effective at the minimum-delay cycle length whereas the existing PASSER II routine is not. At longer cycle lengths, the results are mixed as to either routine being better than the other, but they are favorable toward the STAR1 routine.

Comparison Summary

The PASSER II selected and best solution phasing arrangement did not match the TRANSYT best solution phasing arrangement for any situation. The PASSER II selected and best solution PI was not the TRANSYT best solution for any situation. The heuristic approach, however, did at the minimum-delay cycle length provide at least a good and sometimes an excellent solution compared with the TRANSYT best solution. At longer cycle lengths, the PASSER II best solution showed a degradation in worthiness based on the TRANSYT results.

The results of using the PASSER II green split routine as an initial starting point were mixed. The comparison of the SPLIT1 routine with the STAR1 routine showed that at the minimum-delay cycle length the TRANSYT STAR1 routine provided a lower PI. The differences between the two routines were sometimes small. At the longer cycle lengths, the results showed that the SPLIT1 routine provided a better TRANSYT solution for some situations.

These results using the TRANSYT PIs as the basis for comparison indicate that, at the minimum-delay cycle length for the scenarios, the heuristic approach provided at least a good solution compared with the optimal. At other cycle lengths, the results were mixed.

The TRANSYT best solution is always the minimum value for each cycle length. At the 80-s cycle length, the PASSER solutions are closer to the TRANSYT solutions. The spreads of the PASSER solutions are noticeable for the three cycle lengths. The PI results using the SPLIT1 procedure show the similar spread of the PASSER II solution points. It appears that the PASSER solutions are closer to the TRANSYT best solution at the 80-s cycle length.

The effect of choice of cycle length on the mini-

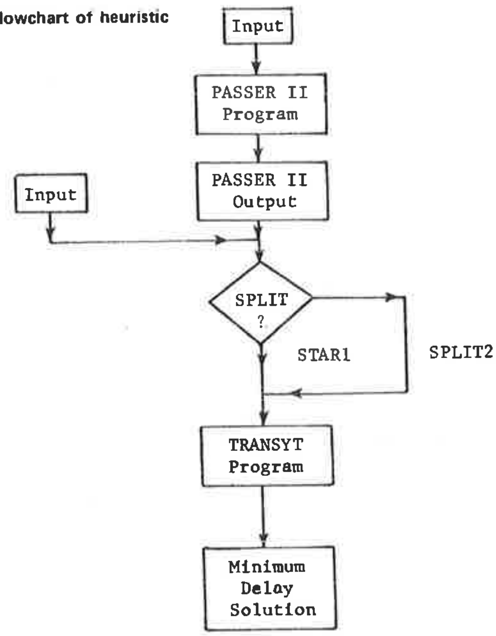


Figure 3. Flowchart of heuristic procedure.

mum-delay solution results is apparent. This would tend to indicate the importance of cycle length in the selection of signal timing parameters for arterial streets. The magnitude of and the differences in the TRANSYT solution results for the PASSER II selected solutions from the TRANSYT evaluation routine give rise to a question as to whether the TRANSYT routine would have any bias that would mask or distort the differences.

CONCLUSIONS AND RECOMMENDATIONS

The overall objective of this paper was to evaluate the selection of a good signal timing plan from a range of multiple-phase sequences, offsets, and cycle lengths for a minimum-delay solution. A heuristic procedure was proposed that uses the PASSER II computer program to select the initial starting point for the TRANSYT6 program. Comparisons were made between the heuristic approach solution and the TRANSYT best solution.

The heuristic procedure, when restricted to the minimum-delay cycle length, did result in at least a good solution compared with the TRANSYT best solution. The comparison between the PASSER II green split and the TRANSYT STAR1 routine produced mixed results when the TRANSYT evaluations were used. Overall, the STAR1 splits produced better results. For specific situations, the PASSER II solutions did result in a better solution.

Conclusions

Because of the evaluation of the heuristic procedure for a limited number of scenarios, an all-inclusive conclusion cannot be made regarding the effectiveness of the heuristic procedure. For the conditions modeled, the heuristic procedure did result in at least a good solution for the minimum-delay optimization. Thus, the heuristic procedure, as illustrated, is a feasible method for developing the signal timing variables for an arterial street. The ability of the heuristic procedure to easily determine phasing sequence, offsets, and green splits for use without complete explicit enumeration provides a useful method. The incorporation of a minimum-delay cycle length procedure should be part of the routine.

Recommendations

Because only an example arterial street was evaluated, the universal validity of the heuristic procedure for all situations or conditions cannot be categorically claimed. Further testing is suggested.

The underlying correspondence and relationship between a progression solution and a minimum-delay solution require further study. Specific recommendations for further investigation, additional research, and improved modeling of the heuristic procedure or signal timing optimization are as follows:

1. The heuristic procedure needs to be researched to consider different volume levels, cycle lengths, and spacings. This would provide additional evaluations for assessing the worthiness of the heuristic approach.
2. The effect of cycle length on the optimal progression, minimum-delay, and heuristic procedure solution needs to be studied further. The inherent intuitive correspondence between a maximum bandwidth progression solution and a minimum-delay solution needs to be further explored.
3. The difference in the PASSER II alternative optimal solutions after optimization in the TRANSYT program requires further exploration.
4. Further modification of the PASSER II program should be examined. A revised green split procedure could be effective and reduce the differences between the PASSER II selected solution and the TRANSYT optimal solution. The incorporation of a minimum-delay cycle length range into the heuristic procedure should be accomplished.

This paper provides a heuristically good procedure for the determination of those signal timing variables that could not be previously determined for a minimum delay solution without complete enumeration or subjective assumption. The component parts and programs for the procedure are readily available and in widespread use. The heuristic procedure can be easily applied and implemented. Its pertinent steps are shown in Figure 3. The heuristic procedure could be easily developed as a combined program with the PASSER II computer program being a preprocessor to the TRANSYT computer program.

As with any general tool or heuristic procedure, it has limitations that have not been fully resolved. However, until optimal or better optimization programs are developed, this procedure can provide the means to determine all the arterial street signal timing variables in an efficient manner.

ACKNOWLEDGMENT

This paper presents a portion of the senior author's dissertation topic at Texas A&M University. The Civil Engineering Department provided the computer resources needed to accomplish this research.

The contents of this paper reflect our views, and we are responsible for the facts and the accuracy of the data presented.

REFERENCES

1. J.H. Kell. Intersection Delay Obtained by Simulating Traffic on a Computer. HRB, Highway Research Record 15, 1963, pp. 73-97.
2. R.L. Vecellio. Traffic Behavior on One-Way Signalized Arterials. Transportation Engineering Journal, ASCE, Vol. 103, No. TE5, Sept. 1977, pp. 575-589.
3. R. Mayer. Cologne's Automatic Traffic Control System. Traffic Engineering and Control, Vol. 4, No. 5, Sept. 1962, pp. 256-259.

4. G. Breenkotter. Hamburg's Traffic Signal Control. Traffic Engineering and Control, Vol. 4, No. 8, Dec. 1962, pp. 433-443.
5. G. Charlesworth. Improving London's Traffic Flow. Traffic Engineering and Control, Vol. 3, No. 10, Feb. 1962, pp. 603-609.
6. H.G. Rosdolsky. A Method for Adaptive Traffic Control. Transportation Research, Vol. 7, No. 1, March 1973, pp. 1-16.
7. B.E. Horn. International Cooperation in Traffic Research: Relief of Inner City Traffic Congestion. Traffic Engineering, Vol. 43, No. 2, Nov. 1972, pp. 32-38.
8. M.G. Davis and W.B. Hirsch. Planning Considerations for Traffic Signal Systems. HRB, Highway Research Record 366, 1971, pp. 29-36.
9. K.L. Bang. Optimal Control of Isolated Traffic Signals. Traffic Engineering and Control, Vol. 17, No. 7, July 1976, pp. 288-292.
10. A.J. Al-Khaliki. Criteria for Defining Sub-Areas for Use in Computer-Controlled Area Traffic Networks. Traffic Engineering and Control, Vol. 16, No. 6, June 1975.
11. E.S.K. Chien and D.W.C. Shen. Optimal Control of Urban Traffic Signals by Means of Band Transportation. In Control in Transportation Systems, American Elsevier, New York, 1976.
12. S.B. Miller and J.D.C. Little. Evaluation and Improvement of Traffic Signal Settings by Simulation. HRB, Highway Research Record 170, 1967, pp. 56-69.
13. M. Longley. A Simulation Study of a Traffic Network Control Scheme. Transportation Research, Vol. 5, No. 1, Jan. 1971, pp. 39-42.
14. J.C. Ramon. New Area Traffic Control System in the City of Barcelona. In Traffic Control and Transportation Systems, American Elsevier, New York, 1974.
15. J.M. Bayley. Some Aspects of Traffic Signal Control. Australian Road Research, Vol. 2, No. 3, March 1965, pp. 23-39.
16. P.J. Tarnoff and P.S. Parsonson. Guidelines for Selecting Traffic Signal Control at Individual Intersections: Volume 1. NCHRP, Interim Rept., July 1979.
17. N. Gartner. Constraining Relations Among Offsets in Synchronized Signal Networks. Transportation Science, Vol. 6, No. 1, Feb. 1972, pp. 88-92.
18. K.W. Huddart. The Importance of Stops in Traffic Signal Progression. Transportation Research, Vol. 3, No. 1, April 1969, pp. 143-150.
19. C. Pinnell. Traffic Control Systems Handbook. FHWA, June 1976.
20. F.V. Webster and R.M. Cobbe. Traffic Signals. Transport and Road Research Laboratory, Tech. Paper 56, Her Majesty's Stationary Office, London, April 1966.
21. J.A. Sosin. Delays at Intersections Controlled by Fixed Cycle Traffic Signals. Traffic Engineering and Control, Vol. 21, Nos. 8-9, Aug.-Sept. 1980, pp. 407-413.
22. D.N. Dewess. Simulation of Traffic Congestion in Toronto. Transportation Research, Vol. 12, No. 3, June 1978.
23. C.J. Messer, H.E. Haenel, and E.A. Keoppe. A Report on the User's Manual for Progression Analysis and Signal System Evaluation Routine: PASSER II. Texas Transportation Institute, Texas A&M Univ., College Station, Res. Rept. 165-14, 1974.
24. R.O. Rogness. Possible PASSER II Enhancements. TRB, Transportation Research Record 881, 1982, pp. 42-48.
25. R.O. Rogness. A Heuristic Programming Approach to Arterial Signal Timing. Texas A&M Univ., College Station, Ph.D. dissertation, Aug. 1981.

Publication of this paper sponsored by Committee on Traffic Signal Systems.

OPAC: A Demand-Responsive Strategy for Traffic Signal Control

NATHAN H. GARTNER

Optimization Policies for Adaptive Control (OPAC) is a computational strategy for real-time demand-responsive traffic signal control. It has the following features: (a) It provides performance results that approach the theoretical optimum, (b) it requires on-line data that can be readily obtained from upstream link detectors, (c) it is suitable for implementation on existing microprocessors, and (d) it forms a building block for demand-responsive decentralized control in a network. Studies undertaken in the development of this strategy and the testing of its performance via the NETSIM simulation model are described.

Urban vehicle traffic as an expression of human behavior is variable in time and space. Therefore, a high degree of adaptiveness is required in the control of such traffic to provide a suitable response to this variability. Ever since the inception of modern traffic signal controls, traffic engineers and signal system designers have attempted to make them as responsive as possible to prevailing traffic conditions. The premise has always been that increased responsiveness leads to improved traffic performance. This premise applies, in broad terms, to single intersection signals as well as arterial and network systems. However, the extent to which traffic responsiveness is achieved depends on a variety of factors, including control hardware, software capabilities, surveillance equipment, and operator qualifications.

With the advent of computerized systems in the mid-1960s, many cities began to deploy centrally controlled and monitored traffic signal systems. Such systems have offered (and still do offer) significant advantages compared with the previously available electromechanical devices. But they also impose a certain rigidity that restricts the opportunities for traffic responsiveness. This has been quite evident in the Urban Traffic Control System (UTCS) experiments in Washington, D.C., as well as in similar experiments conducted in Canada and in Great Britain (1-3). A review of the causes of this failure and a prescription for its alleviation are presented elsewhere (4).

The emergence of microprocessor technologies is drastically changing the traffic signal control field and opening up new horizons and opportunities for demand-responsive control that were not imaginable in the past. It is now feasible to develop much more sophisticated systems than before, systems that would offer a great deal of responsiveness, would work automatically, and would almost eliminate the need for operator intervention.

This paper describes studies that have been undertaken in the development of a strategy that would serve as a building block for demand-responsive decentralized traffic signal control. The strategy, called Optimization Policies for Adaptive Control (OPAC), was developed in stages. First, a dynamic programming (DP) procedure was used to establish a standard of performance for demand-responsive control, since the DP technique is capable of generating optimal control strategies. Next, a simplified procedure was developed that replicates the performance of DP yet relinquishes its extensive computational requirements so that it becomes suitable for on-line implementation. In the third stage, the procedure was further refined by applying a rolling horizon approach. In this way, only readily available data are required and a practical method for demand-responsive control is obtained. This paper is based on a research report prepared for the U.S. Department of Transportation (5).

REVIEW

Forms of Traffic Signal Control

There are three basic forms of traffic signal control: pretimed, semiactuated, and fully actuated. The latter is further subdivided into fully actuated with volume-density control and without volume-density control. According to Orcutt (6), pretimed control is used primarily in the central business district, especially where a network of signals must be coordinated. This is not a good strategy where more than three phases are required. Orcutt defines actuated signals as equipment that responds to actual traffic demand of one or more movements as registered by detectors. If all movements are detected, the control is called fully actuated. He also states that fully actuated control should normally be used at isolated intersections.

The National Electrical Manufacturers Association (7) provides the following definitions for the four types of control:

1. The pretimed controller assembly is a controller assembly for the operation of traffic signals with predetermined fixed cycle length(s), fixed interval duration(s), and fixed interval sequence(s).
2. The semi-traffic-actuated controller assembly is a type of traffic-actuated controller assembly in which means are provided for traffic actuation on one or more but not all approaches to the intersection.
3. The full-traffic-actuated without volume density controller assembly is a type of traffic-actuated controller assembly in which means are provided for traffic actuation on all approaches to the intersection. The fully actuated controller without volume density has three settings for the determination of green timing on an actuated phase: (a) initial interval, the first timed portion of the green interval, which is set in consideration of the storage vehicles waiting between the sensing zone of the approach vehicle detector and the stopline, (b) extension interval (gap), a portion of the green interval whose timing shall be reset with each vehicle actuation and shall not commence to time again until the vehicle actuation signal is removed from the input to the controller unit, and (c) maximum extension, a time setting that shall determine the length of time that this phase may be held green in the presence of an opposing serviceable call.
4. In the full-traffic-actuated with volume density controller assembly, the volume-density operation shall include a form of variable initial timing and gap reduction timing. The effect on the initial timing shall be to increase the timing in a manner that depends on the number of vehicle actuations stored on this phase while its signal is displaying the yellow or red. The effect on the extensible portion shall be to reduce the allowable gap between successive vehicle actuations in a manner that is related to the delay of the first vehicle arriving on a conflicting phase.

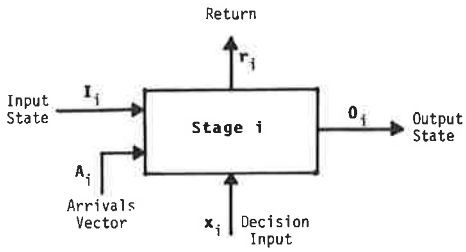
When properly calibrated, traffic-actuated signals in their various forms provide considerable advantages over fixed-time equipment and are widely used. Reports by Staunton (8) and Tarnoff and Parsonson (9) provide a comprehensive evaluation of actuated signal controls. It is apparent, however, that the methods of actuation are of an ad hoc nature and cannot provide the best possible performance. Moreover, these forms of actuation are not suitable for signal systems where demand-responsiveness and coordination are needed simultaneously.

Analytic Modeling of the Intersection Control Problem

There is a tremendous variety of modeling problems associated with the optimal control of traffic intersections, but only a limited number of special cases have been studied analytically. The most common approach is to determine settings for a fixed-cycle light that minimize the average delay per car, assuming constant arrival rates (10,11). Gazis and Potts (12) obtained conditions for the optimal control of an intersection that becomes oversaturated for some finite length of time, and the model has been extended by Gazis (13) to two intersections. The same modeling approach has also been studied by Michalopoulos and Stephanopoulos (14). Dunne and Potts (15,16) developed time-varying control algorithms for an undersaturated intersection with constant arrivals that guarantee that, for any initial state, the system will eventually reach a limit cycle for which the average equilibrium delay per car is a minimum. In all of these models, the dynamics of the control policy are not responsive to the dynamics of the traffic flow process since there is no real-time traffic flow information. The traffic flow process is represented by a single value (the expected flow rate), a statistical distribution (Poisson, binomial, etc.), and the initial conditions (the initial queue lengths) or, in case of oversaturation, by a smooth function of demand versus time. Obviously, none of these models can take advantage of the time-variant features of individual vehicle arrival times.

A dynamically self-optimizing strategy has been proposed by Miller (17). In this strategy, a decision whether to extend a phase is repeatedly made at very short fixed intervals h by the examination of a delay-based control function. This function estimates the difference in vehicle seconds of delay between the gain to the extra vehicles that will be allowed to cross the intersection during an exten-

Figure 1. Stage in the DP process.



sion of h seconds and the loss to the queuing vehicles on the cross street that results from the extension (h is 1-2 s long). A similar approach was also proposed by van Zijverden and Kwakernaak (18). Bang and Nilsson (19) implemented and field tested Miller's strategy and showed that significant gains can be obtained compared with fixed-time and vehicle-actuated control at isolated intersections. However, since this method has a very short projection horizon and corresponding optimization interval, it does not appear to lend itself to implementation in a network of intersections and furthermore does not ensure overall optimality of the control strategy. Because of its capability for multistage decisionmaking, dynamic programming is an attractive candidate technique for dynamic optimal signal control. Two DP models have been proposed in the literature for optimal signal control: Grafton and Newell (20) developed a continuous-time model, and Robertson and Bretherton (21) used a discrete-time model. The first model chooses to minimize an infinite-horizon total discounted delay function. The second model minimizes the total delay aggregated over all intervals of a finite horizon. This paper first develops and investigates a discrete-time version of DP similar to the second model.

DYNAMIC PROGRAMMING APPROACH

DP is a mathematical technique used for the optimization of multistage decision processes. In this technique, the decisions (or control values) that affect the process are optimized in stages rather than simultaneously. This is done by dividing the original decision-control problem into small subproblems (stages) that can then be handled much more efficiently from a computational standpoint. DP is a systematic procedure for determining the combination of decisions that maximizes overall effectiveness or minimizes overall disutility. It is based on the principle of optimality enunciated by Bellman (22): "An optimal policy has the property that whatever the initial state and initial decision are, the remaining decisions must constitute an optimal policy with regard to the state resulting from the first decision."

Consider a single intersection with signal phases that consist of effective green times and effective red times only. All traffic arrivals on the approaches to the intersection are assumed to be known for a finite horizon length. The optimization process is decomposed into N stages, where each stage represents a discrete time interval (such as 5 s).

A typical stage i is shown in Figure 1. At stage i we have an input state vector I_i, arrivals vector A_i, output state vector O_i, input decision variable x_i, economic return (cost) output r_i, and a set of transformations:

$$O_i = T_i(I_i, A_i, x_i)$$

$$r_i = R_i(I_i, A_i, x_i)$$

The state of the intersection is characterized by the state of the signal (green or red) and by the queue length on each of the approaches. Assuming a two-phase signal, the input decision variable indicates whether the signal is to be switched at this stage (x = 1) or remain in its present state (x = 0). The return cost output is the intersection index of performance (the total delay time), which has to be minimized. The functional relation between the input and output variables is based on the queuing-discharge processes at the intersection--i.e., the inflow and outflow relative to the signal settings.

DP optimization is carried out backwards--i.e., starting from the last time interval and backtracking to the first, at which time an optimal switching policy for the entire time horizon can be determined. The switching policy consists of the sequence of phase switch-ons and switch-offs throughout the horizon.

The recursive optimization function is given by the following equation:

$$f_i^*(I_i) = \min_{x_i} [R_i(I_i, A_i, x_i) + f_{i+1}^*(I_i, A_i, x_i)] \qquad (1)$$

The return at state i is the queuing delay incurred at this stage and is measured in vehicle-interval units. Thus, when the optimization is complete at stage i = 1, we have $f_1^*(I_1)$, which is the minimized total delay over the horizon period for a given input state I_1. Since the initial conditions at stage 1 are specified (i.e., the queue lengths on all approaches are given as well as the initial signal status), the optimal policy can be retraced by taking a forward pass through the stored arrays of $x_i^*(I_i)$. The policy consists of the optimal sequence of switching decisions (x_i^*, i = 1, ..., N) at all stages of the optimization process.

An example of the demand-responsive control strategy calculated by this approach is shown in Figure 2 for a 5-min horizon length. The signal is two-phase and only two approaches are considered: A and B. The figure shows the arrivals on the approaches, the optimal switching policies, and the resulting queue-length histories. The signal timings appear as hatched (red) and blank (green) areas, including an all-red overlapping red interval at each switching point. The total performance index (PI) is 196 vehicle intervals. This is the best possible policy for the given arrival patterns.

SIMPLIFIED APPROACH

The DP approach for calculating demand-responsive optimal control policies requires advance knowledge of arrival data for the entire horizon period. This is far beyond what can reasonably be expected to be obtained from available surveillance systems. Moreover, the optimization requires an extensive computational effort and, since it is carried out backwards in time, it precludes the opportunity for updating the input data or correction of future control policies. Thus, although the DP approach ensures global optimality of the calculated control strategies, it is unsuitable for on-line use. This approach also produces a good deal of information that is not used. Optimal policies are obtained for all possible initial conditions, yet only one of these policies applies in practice.

Consequently, this research set out to develop a simplified optimization procedure that would be amenable to on-line implementation yet would provide results comparable in quality to those obtained via DP. The procedure has the following basic features:

1. The optimization process is divided into se-

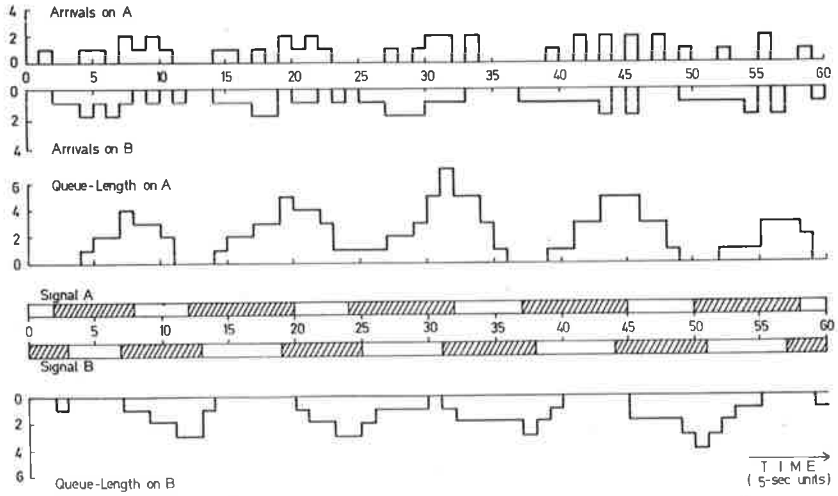
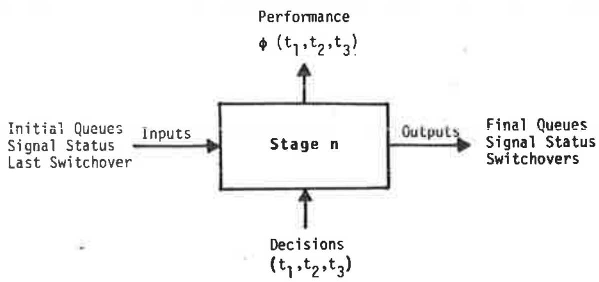


Figure 2. Optimal demand-responsive control strategy for a two-phase signal generated by DP (5-min data, PI = 196 vehicle intervals).

Figure 3. Information and decision flow at stage n of simplified optimization procedure.



quential stages of T seconds. The stage length is in the range of 50-100 s (i.e., similar to a cycle length for a fixed-time traffic signal) and consists of an integral number of the basic time intervals.

2. During each stage, at least one signal change (switchover) is required and up to three switchovers are allowed. This is designed to provide sufficient flexibility for deriving an optimal demand-responsive policy.

3. For any given switching sequence at stage n, a performance function is defined on each approach that calculates the total delay during the stage (in vehicle intervals):

$$\phi_n(t_1, t_2, t_3) = \sum_{i=1}^{k} (Q_o + A_i - D_i) \tag{2}$$

where

Q_o = initial queue,
A_i = arrivals during interval i,
D_i = departures during interval i, and
(t_1,t_2,t_3) = possible switching times during this stage.

Hence, ϕ measures the area enclosed between the cumulative arrivals and cumulative departures curves.

4. The optimization procedure used for solving the problem is an optimal sequential constrained search (OSCO) method (23). The objective function (total delay) is evaluated sequentially for all feasible switching sequences. At each iteration, the current PI (objective value) is compared with the previously stored value and, if lower, replaces it. The corresponding switching point times and final queue lengths are also stored. At the end of the search, the values in storage are the optimal solution.

The optimal switching policies are calculated independently for each stage in a forward sequential manner for the entire process (i.e., one stage after another). Therefore, this approach (unlike the DP approach) can be used in an on-line system. Figure 3 shows the information and decision flow at a typical stage n.

A comparison of computational results indicates that the simplified approach provides results that are very close to the optimum obtained by the DP approach. In most cases, the difference in the PI for the entire horizon is less than 10 percent. This is very encouraging, since the computational requirements (and the traffic data that are needed) are much reduced. An example is shown in Figure 4.

ROLLING HORIZON APPROACH

The previous section identified a basic building block for demand-responsive decentralized control, a simplified optimization technique for determining optimal switching policies in a time stage of T seconds. The technique requires future arrival information for the entire stage, which in practice is difficult to obtain with reliability. To reduce these requirements in such a way that one can use only available flow data and yet preserve the performance of the computational procedure, the rolling horizon (or rolling schedule) concept is introduced. This concept is used by operations research analysts in production-inventory control (24) and is here applied to the traffic control problem. The stage length consists of k intervals, which is the projection horizon, the period for which traffic flow information is needed. From upstream detectors, actual arrival data can be obtained for a near-term period of r intervals at the "head" of the stage. For the next (k-r) intervals, the "tail" of the stage, flow data are obtained from a model. An optimal policy is calculated for the entire stage but implemented only for the head section. The projection horizon is then shifted (rolled) r units ahead, new flow data are obtained for the stage (head and tail), and the process is repeated, as shown in Figure 5.

The basic steps in the process are as follows:

No.	Step
0	Determine stage length k and roll period r
1	Obtain flow data for first r intervals (head) from detectors and calculate flow data for next k-r intervals (tail) from model and detectors
2	Calculate optimal switching policy for entire stage by OSCO
3	Implement switching policy for roll period (head) only
4	Shift projection horizon by r units to obtain new stage; repeat steps 1-4

The computer program that implements this process has been named Optimization Policies for Adaptive Control or OPAC (5). The OPAC strategy was tested by using actual arrivals for the head of the stage and two types of models for the tail: (a) variable-tail, where projected actual arrivals are taken for the tail, and (b) fixed-tail, where the tail consists of a fixed flow equal to the average flow rate during the period.

The first model was used only to test the rolling horizon concept and compare the results with previous experimentations. The second model is of primary interest since it represents a practical approach to implementing OPAC. Measurements from upstream detectors can be used for head data and smoothed average flows for tail data, both of which are readily available. The head data are continuously updated in the rolling process. As one would expect, the variable-tail OPAC produces policies that are better than those produced by the simplified approach and, in most cases, replicate the standards obtained with the DP approach. Fixed-tail OPAC, although it uses smoothed data, comes very close to the optimal and represents a feasible and promising approach to real-time control. In particular, OPAC offers rather substantial savings in comparison with a fixed-time strategy such as Webster's (10) for the same total intersection volume (see Figure 6). These savings are impressive even when compared with strategies such as vehicle-actuated or Miller's (17), which are only 15-25 percent better than Webster's.

Another test of OPAC was conducted by using a special version of the NETSIM simulation model in which arriving traffic streams can be externally specified. The simulation logic was used to compare the performance of the original settings with that of the OPAC-generated control policies for the same arrival data. Five different 30-min data sets of a signal-controlled intersection in Tucson, Arizona, were tested. The results are given in Table 1. The OPAC policies provided a reduction of 30-50 percent of the initial delay. Corresponding improvements are noted in speed, which is averaged over all links of the simulated mininetwork. This contains large portions of travel time that are not subject to influence by the control strategy. Nevertheless, increases in average speeds ranged from 10 to 20 percent.

CONCLUSIONS

On-line traffic control strategies should be capable of providing results that are better than those produced by the off-line methods. The studies reported in this paper indicate that substantial benefits can be achieved with truly responsive strategies.

The OPAC strategy offers a feasible and very promising approach to real-time control. The strategy is designed to make use of readily available data, produces control policies that are almost as effective as those that would be obtained under ideal conditions, and has very reasonable computational requirements. It is well-suited for implementation via microprocessor technologies (25).

What is perhaps of even greater significance is the OPAC traffic flow model. It considers the entire projection horizon in the optimization process and therefore should be amenable for application in a demand-responsive, decentralized, flexibly coordinated system. In such a system, one would use the analysis capabilities of OPAC to structure the flows in the network so that one can preserve coordination on the one hand while taking advantage of the ever present variations in flows on the other. Thus, the system would require both local analysis capabilities and communication with adjacent controllers. A sketch of the envisioned information flow is shown in Figure 7. The development of such a system is the goal of the next phase of this research.

Figure 4. Demand-responsive policies generated by simplified approach with 60-s projection horizon.

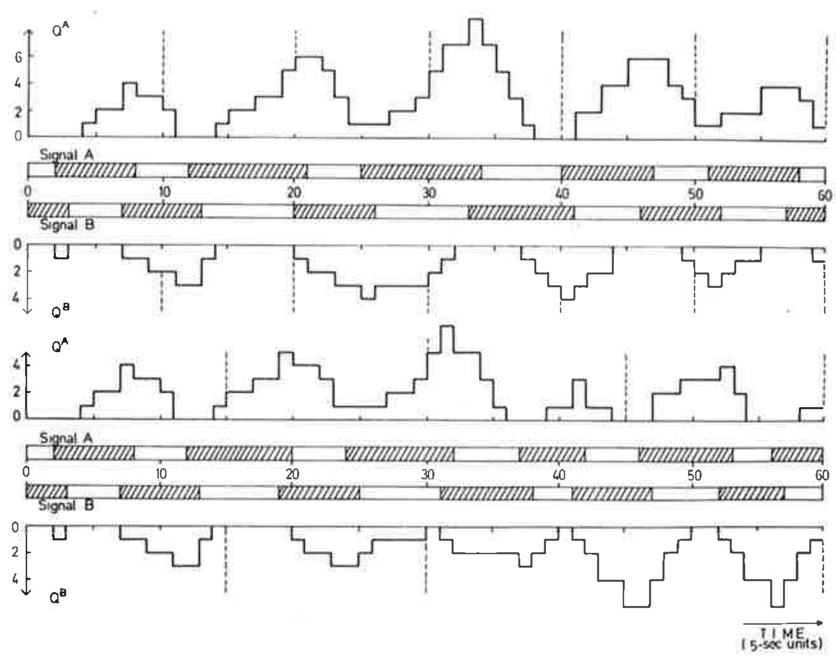


Table 1. NETSIM simulation results (30-min data sets) for a Tucson, Arizona, intersection.

Data Set	Avg Delay: Original Settings (s/vehicle)	Avg Delay: OPAC Policies (s/vehicle)	Avg Delay: Percent of Original	Avg Speed: Original Settings (mph)	Avg Speed: OPAC Policies (mph)	Avg Speed: Percent of Original
1	44.92	23.70	52.8	22.02	26.54	120.5
2	37.74	22.52	59.7	23.35	27.06	115.9
3	33.98	23.46	69.0	24.07	26.65	110.7
4	41.43	21.61	52.2	22.60	26.98	119.4
5	40.45	23.59	58.3	22.90	26.63	116.3

Figure 5. Rolling horizon approach.

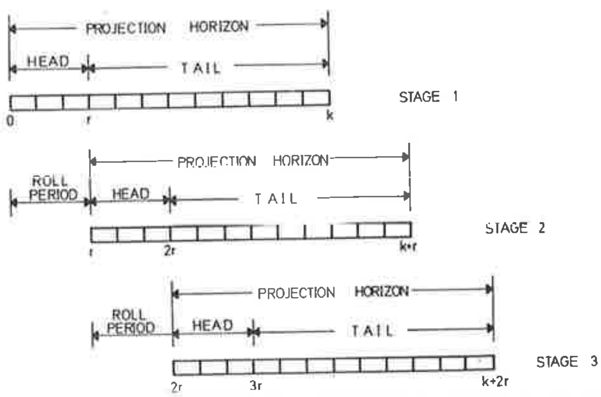


Figure 6. Comparison of average delay per vehicle at a single intersection for two strategies.

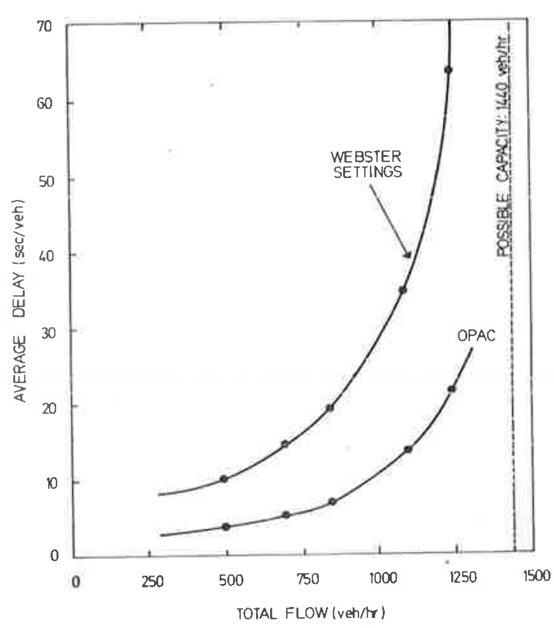
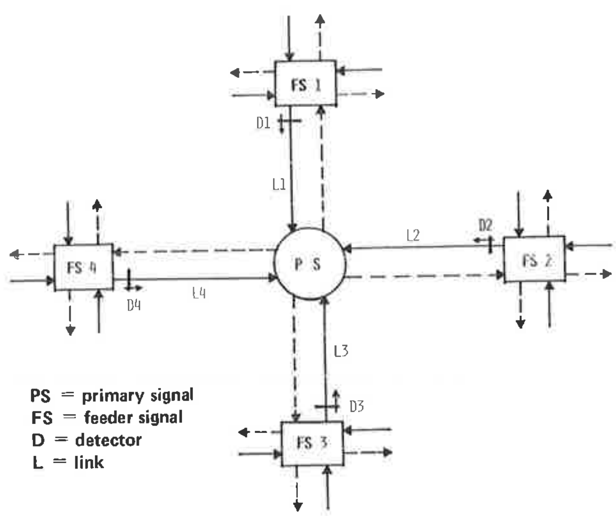


Figure 7. Information flow for demand-responsive decentralized control concept.



ACKNOWLEDGMENT

This paper is based on a research project conducted under the sponsorship of the Office of University Research, U.S. Department of Transportation. The opinions expressed in the paper are mine and not necessarily those of the sponsoring agency.

I would like to thank Stephen L. Cohen of the Federal Highway Administration for his assistance in conducting the NETSIM simulation experiments.

REFERENCES

1. J. MacGowan and I.J. Fullerton. Development and Testing of Advanced Control Strategies in the Urban Traffic Control System. Public Roads, Vol. 43, Nos. 2,3,4, 1979-1980.
2. J. Holroyd and D.I. Robertson. Strategies for Area Traffic Control Systems Present and Future. Transport and Road Research Laboratory, Crowthorne, Berkshire, England, Rept. LR569, 1973.
3. Improved Operation of Urban Transportation Systems. Corporation of Metropolitan Toronto, Toronto, Ontario, Canada, Vol. 1, March 1974, Vol. 2, Nov. 1975, Vol. 3, Nov. 1976.
4. N.H. Gartner. Urban Traffic Control Strategies: The Generation Gap. Proc., 2nd International ATEC Congress, Paris, France, April 1980.
5. N.H. Gartner. Demand-Responsive Decentralized Urban Traffic Control: Part I--Single-Intersection Policies. Office of University Research, U.S. Department of Transportation, Rept. DOT-RSPA-DPB-50-81-24, Feb. 1982.
6. F.L. Orcutt. A Primer for Traffic Signal Selection. Public Works--City, County and State, March 1975, pp. 76-80.
7. Traffic Control Systems. National Electrical Manufacturers Assn., Washington, DC, Standards Publ. TS1, 1976.
8. M.M. Staunton. Vehicle Actuated Signal Controls for Isolated Locations. AN FORAS

FORBARTHA, National Institute for Physical Planning and Construction Research, Dublin, Ireland, No. RT-159, Sept. 1976.
9. P.J. Tarnoff and P.S. Parsonson. Guidelines for Selecting Traffic Signal Control at Individual Intersections. NCHRP, July 1979.
10. F.V. Webster. Traffic Signal Settings. Her Majesty's Stationery Office, London, Road Res. Tech. Paper 39, 1958.
11. A.J. Miller. Settings for Fixed-Cycle Traffic Signals. Operational Research Quarterly, Vol. 14, 1963, pp. 373-386.
12. D.C. Gazis and R.B. Potts. The Oversaturated Intersection. Proc., 2nd International Symposium on Theory of Road Traffic Flow (J. Almond, ed.), Organization for Economic Cooperation and Development, Paris, 1965.
13. D.C. Gazis. Optimum Control of a System of Oversaturated Intersections. Operations Research, Vol. 12, 1964, pp. 815-831.
14. P.G. Michalopoulos and G. Stephanopoulos. An Algorithm for Real-Time Control of Critical Intersections. Traffic Engineering and Control, 1979, pp. 9-15.
15. M.C. Dunne and R.B. Potts. Algorithm for Traffic Control. Operations Research, Vol. 12, 1964, pp. 870-881.
16. M.C. Dunne and R.B. Potts. Analysis of Computer Control of an Isolated Intersection. Proc., 3rd International Symposium on Theory of Traffic Flow (L.C. Edie and others, eds.), American Elsevier, New York, 1967.
17. A.J. Miller. A Computer Control System for Traffic Networks. Proc., 2nd International Symposium on Theory of Road Traffic Flow (J. Almond, ed.), Organization for Economic Cooperation and Development, Paris, 1965.
18. J.D. van Zijverden and H. Kwakernaak. A New Approach to Traffic-Actuated Computer Control of Intersections. Proc., 4th International Symposium on Theory of Traffic Flow (W. Leutzbach and P. Baron, eds.), Strassenbau und Strassenverkehrstechnik, Heft 86, Bonn, Federal Republic of Germany, 1969.
19. K.L. Bang and L.E. Nilsson. Optimal Control of Isolated Traffic Signals. Proc., Australian Road Research Board, Vol. 8, 1976, pp. 16-24.
20. R.B. Grafton and G.F. Newell. Optimal Policies for the Control of an Undersaturated Intersection. Proc., 3rd International Symposium on Theory of Traffic Flow (L.C. Edie and others, eds.), American Elsevier, New York, 1967.
21. D.I. Robertson and R.D. Bretherton. Optimum Control of an Intersection for any Known Sequence of Vehicle Arrivals. Presented at 2nd IFAC/IFIP/IFORS Symposium on Traffic Control and Transportation Systems, North-Holland, Amsterdam, 1974, pp. 3-17.
22. R.D. Bellman. Dynamic Programming. Princeton Univ. Press, Princeton, NJ, 1957.
23. S.S. Rao. Optimization Theory and Applications. Wiley Eastern, New Delhi, India, 1978.
24. H.M. Wagner. Principles of Operations Research, 2nd ed. Prentice-Hall, Englewood Cliffs, NJ, 1977.
25. N.H. Gartner. Prescription for Demand-Responsive Urban Traffic Control. TRB, Transportation Research Record 881, 1982, pp. 73-75.

Publication of this paper sponsored by Committee on Traffic Signal Systems.

Concurrent Use of MAXBAND and TRANSYT Signal Timing Programs for Arterial Signal Optimization

S. L. COHEN

A number of computer programs have been developed for the purpose of optimizing signal timing. All of the current programs, however, have some deficiencies. The TRANSYT program, which is the most widely used, has a good traffic model and optimizes green phase time. However, it does not get a globally optimal solution, optimize phase sequence, or really optimize cycle length. The MAXBAND program, which optimizes arterial bandwidth, does all of the above but is deficient in that green time is not optimized and the traffic model used is oversimplified. It is shown that a feasible way to overcome these deficiencies is to use the MAXBAND program to develop an initial timing plan for TRANSYT. This initial timing plan includes both cycle length and phase sequence optimization. The timing plans produced by the TRANSYT and MAXBAND programs separately were compared with the combined timing plans by using the NETSIM model. The results indicate that a substantial improvement in measures of effectiveness is obtained with the combined timing plans.

In recent years, there has been increasing emphasis on conserving energy, mostly due to the gasoline shortage crises of 1973 and 1979. One of the most cost-effective traffic engineering techniques for improving traffic flow and, hence, fuel efficiency is improvement of signal timing (1). In support of this goal, the Federal Highway Administration (FHWA) undertook the National Signal Timing Optimization Project (2). As part of this project, the TRANSYT 7 program (3) was modified so that it could be more easily used by American traffic engineers to develop signal timing plans for coordinated signal systems. The revised program is called TRANSYT 7F (4).

In parallel with the TRANSYT 7F activity, another approach to arterial signal timing, using the principal of maximal green bandwidth, has been pursued. This has resulted in the development of the MAXBAND program (5).

The purpose of the work described in this paper was to explore the advantages and disadvantages of the TRANSYT and MAXBAND programs as they are applied to arterials and to demonstrate that using both programs to develop timing plans can partly overcome the disadvantages of each of them.

DESCRIPTION OF PROGRAMS

TRANSYT

The TRANSYT program includes an excellent traffic model that uses network geometry and traffic flows to make estimates of two measures of effectiveness (MOEs)--delay and stops. The hill-climbing optimization procedure adjusts offsets and green times separately so as to minimize the value of a performance index (PI), which is equal to the weighted sum of stops and delay.

Although field tests (2) and simulation tests (6) indicate that TRANSYT produces good signal timing plans, it also has a number of deficiencies:

1. The hill-climbing optimization algorithm does not generally guarantee that a global optimum for the PI will be achieved and therefore does not guarantee that the "best" signal timing plan will be found. This is because the signal timing problem in general has a solution space for the PI, which consists of a number of local optima. It is computationally infeasible, when using the hill-climbing technique, to search through all local optima to find the best one.
2. TRANSYT requires a signal timing plan as a starting solution. Because of item 1 above, the quality of the final signal settings often depends on the starting solution.
3. TRANSYT does not really optimize cycle length. One can run the program for several different cycle lengths and select the one with the best PI.
4. However, because of item 1 above, there is no way of knowing whether the selected cycle length is the best one or whether, for that cycle length, a solution was found that was closer to the global optimum than the solutions found for the other cycle lengths scanned.
5. The sequence of left-turn phases and through phases is not optimized. At signalized intersections where left-turn phases are used, there are four possible combinations for the left-turn phases and through phases in both directions: (a) left-turn phases in both directions preceding the two-directional through phase (lead-lead), (b) left-turn phases in both directions following the two-directional through phases (lag-lag), (c) left-turn phase in the inbound direction preceding the two-directional through phase and left-turn phase in the outbound direction following the two-directional through phase (lead-lag), and (d) left-turn phase in the inbound direction following the two-directional through phase and left-turn phase in the outbound direction preceding the two-directional through phase (lag-lead).

MAXBAND

The MAXBAND program uses as its traffic model the maximal green bandwidth principle (7). This is combined with a powerful mathematical programming algorithm, mixed integer linear programming (MILP), to obtain offsets, cycle length, and left-turn phase sequence, which maximize the weighted sum of bandwidths in both directions on an arterial. The program also has the capability to allow small deviations from the arterialwide progression speed on individual links, a process referred to as speed search.

Unlike TRANSYT, the MAXBAND program obtains a global optimum, requires no starting solution, and optimizes cycle length and phase sequence. However, MAXBAND has the following deficiencies:

1. The traffic model is oversimplified. No account is taken of secondary flows turning from side streets, platoon dispersion, turning traffic, or platoon shape. For this reason, it is not generally true that maximizing bandwidth minimizes such MOEs as stops or delay.
2. Green phase times are not optimized. This is because bandwidth provides no criteria for setting green times on the side street.

Summary

It is evident that the two programs described above are complementary; that is, the weaknesses of one are the strengths of the other and vice versa. Thus, it would appear likely that an approach to developing signal timing plans for arterials that used both programs might provide better signal settings than either program could provide separately. It is the purpose of this work to demonstrate the validity of this hypothesis.

EXPERIMENTAL DESIGN

A series of experiments was performed to test the advantages of using both MAXBAND and TRANSYT. The experiments were as follows:

1. TRANSYT optimization of offsets using only the default starting solution (i.e., offset = 0 for A-phase green on the arterial),
2. MAXBAND-optimized offsets without speed search as a starting solution for TRANSYT,
3. MAXBAND-optimized offsets with speed search as a starting solution for TRANSYT,
4. MAXBAND-optimized cycle length used in TRANSYT,
5. MAXBAND-optimized phase sequence used in TRANSYT, and
6. Combinations of experiments 2 and 4, 5 and 6, and 3, 4, and 5.

The purpose of running these sets of experiments was to determine the incremental effects of optimizing each of the traffic control parameters--cycle length and phase sequence--separately.

A set of green times was computed initially by using the algorithm in MAXBAND and was held fixed in both programs. After the above experiments had been performed, a green time optimization was performed by TRANSYT. Two test arterials for which data were available were selected. The major criterion for selection was the presence of left-turn bays at most of the intersections so that the phase sequence optimization capability of MAXBAND could be fully tested. The first arterial, Hawthorne Boulevard in Torrance, California, has eight intersections; the second arterial, University Avenue in Provo, Utah, also had eight intersections.

A total of 16 signal timing plans were developed for each arterial based on experiments 1-5 above. The plans were then compared by using the NETSIM microscopic traffic simulation model (7) as the test bed. One problem that arose concerned the weighting of the two directions in the MAXBAND runs. This arises from the MAXBAND capability of allowing imposition of a wider bandwidth in one direction than in the other. Some preliminary runs on NETSIM indicated that a weighting factor of 10/1 of the southbound direction over the northbound direction on Hawthorne (i.e., the bandwidth in the southbound direction is up to 10 times the bandwidth in the northbound direction) and 1/1 of the southbound direction over the northbound direction on University gave good results. However, as will be seen in the discussion of results later in this paper, the effect of these assumptions was minor.

DESCRIPTION OF ARTERIALS

The section of Hawthorne Boulevard used in this study has four lanes in each direction and two-lane left-turn bays on six of the intersection approaches. All other approaches on the arterial have one-lane left-turn bays. Volumes were about 2800 vehicles/h in the southbound direction and 1400 vehicles/h in the northbound direction. Signal spacing varied from 500 to 1300 ft. Signalization included left-turn phases in both directions on the arterial and single phasing on the side streets. The existing 100-s cycle length was used except for experiments in which cycle length was optimized. In those experiments, a range of 80-110 s was searched. Traffic patterns consisted heavily of through traffic on the arterial and relatively minor secondary flow and turning traffic (except at intersection 10, where turning movements on and off the arterial were heavier). A progression speed of 45 mph was used.

The section of University Boulevard used in this study has two lanes in each direction and one-lane turn bays on all arterial approaches. Volumes are about 900 vehicles/h in the northbound direction and about 850 vehicles/h in the southbound direction. Most of the traffic, however, consists of vehicles that turn on to the arterial from the side streets so that at most intersections secondary flow is high. Turning movements from the arterial are also substantial. Signalization included left-turn phases in both directions on all arterial approaches and single phasing on the side streets. The existing 80-s cycle length was used except for experiments in which cycle length was optimized. In those experiments, a range of 70-100 s was searched. Signal spacing varied from 500 to 1450 ft. A progression speed of 30 mph was used.

RESULTS

The results for each experiment are given in Table 1 for Hawthorne and in Table 2 for University. A number of observations can be made based on the results:

1. The assumption of a south/north bandwidth ratio of 10/1 on Hawthorne for MAXBAND turns out to be unimportant, as can be seen by looking at the result of experiment 12, in which all optimization capabilities of MAXBAND were used. Here, the southbound bandwidth equaled the shortest green in that direction so that the northbound bandwidth received any further improvement available. The resultant ratio, as indicated by Table 1, would be 1.5, which is easily justifiable by the south/north volume ratio of 2/1.

2. TRANSYT and NETSIM did not give the same answer in many experiments with regard to the relative quality of MAXBAND and TRANSYT results. For instance, compare experiments 1 and 2 on Hawthorne

Table 1. Results for Hawthorne Boulevard.

Exp. No.	Optimization Program	Source of Initial Offsets	Optimization: Cycle Length	Optimization: Phase Sequence	Speed Search	Cycle Length (s)	Delay (s/vehicle)	Stops (%)	Fuel Efficiency (miles/gal)	Bandwidth Percentage of Cycle: Southbound	Bandwidth Percentage of Cycle: Northbound	TRANSYT PI
1	MAXBAND	None	No	No	No	100	68.33	1.77	11.37	0.468	0.047	112.6
2	TRANSYT	Default	No	No	No	100	71.47	1.81	11.44	NA	NA	106.7
3	TRANSYT	MAXBAND	No	No	No	100	60.82	1.51	11.83	NA	NA	96.1
4	MAXBAND	None	No	No	Yes	100	63.11	1.60	11.65	0.526	0.053	110.6
5	TRANSYT	Default	No	No	Yes	100	61.21	1.54	11.82	NA	NA	95.7
6	MAXBAND	None	Yes	No	No	80	59.03	1.68	11.65	0.539	0.068	85.8
7	TRANSYT	Default	Yes	No	No	80	60.73	1.68	11.62	NA	NA	86.3
8	TRANSYT	MAXBAND	Yes	No	No	80	58.87	1.69	11.69	NA	NA	83.4
9	MAXBAND	None	No	Yes	No	100	58.70	1.50	11.77	0.539	0.176	108.4
10	TRANSYT	Default	No	Yes	No	100	67.34	1.68	11.68	NA	NA	102.1
11	TRANSYT	MAXBAND	No	Yes	No	100	57.45	1.48	11.98	NA	NA	94.1
12	MAXBAND	None	Yes	Yes	Yes	80	53.24	1.58	11.99	0.539	0.354	87.5
13	TRANSYT	Default	Yes	Yes	Yes	80	54.44	1.58	11.96	NA	NA	78.6
14	TRANSYT	MAXBAND	Yes	Yes	Yes	80	55.15	1.60	11.96	NA	NA	79.1
15[a]	TRANSYT	MAXBAND	Yes	Yes	Yes	80	50.14	1.38	12.16	NA	NA	78.0
16[a]	MAXBAND	None	Yes	Yes	Yes	80	48.24	1.33	12.28	0.506	0.353	-

[a]Green time optimized by TRANSYT.

Table 2. Results for University Boulevard.

Exp. No.	Optimization Program	Source of Initial Offsets	Optimization: Cycle Length	Optimization: Phase Sequence	Speed Search	Cycle Length (s)	Delay (s/vehicle)	Stops (%)	Fuel Efficiency (miles/gal)	Bandwidth Percentage of Cycle: Southbound	Bandwidth Percentage of Cycle: Northbound	TRANSYT PI
1	MAXBAND	None	No	No	No	80	41.67	1.44	9.45	0.192	0.192	84.8
2	TRANSYT	Default	No	No	No	80	40.89	1.42	9.54	NA	NA	77.4
3	TRANSYT	MAXBAND	No	No	No	80	40.53	1.40	9.57	NA	NA	77.1
4	MAXBAND	None	No	No	Yes	80	41.18	1.44	9.51	0.214	0.214	84.5
5	TRANSYT	Default	No	No	Yes	80	40.67	1.40	9.55	NA	NA	77.1
6	MAXBAND	None	Yes	No	No	76	39.46	1.44	9.59	0.211	0.211	83.0
7	TRANSYT	Default	Yes	No	No	76	39.51	1.40	9.65	NA	NA	74.0
8	TRANSYT	MAXBAND	Yes	No	No	76	38.45	1.38	9.73	NA	NA	73.9
9	MAXBAND	None	No	Yes	No	80	38.78	1.33	9.69	0.305	0.305	82.0
10	TRANSYT	Default	No	Yes	No	80	40.90	1.40	9.53	NA	NA	78.6
11	TRANSYT	MAXBAND	No	Yes	No	80	40.31	1.36	9.62	NA	NA	77.7
12	MAXBAND	None	Yes	Yes	Yes	70	33.06	1.23	10.09	0.357	0.357	71.0
13	TRANSYT	Default	Yes	Yes	Yes	70	35.01	1.32	9.97	NA	NA	68.3
14	TRANSYT	MAXBAND	Yes	Yes	Yes	70	35.48	1.29	9.95	NA	NA	70.0
15[a]	TRANSYT	MAXBAND	Yes	Yes	Yes	70	33.68	1.25	10.12	NA	NA	64.6
16[a]	MAXBAND	None	Yes	Yes	Yes	70	32.36	1.23	10.14	0.287	0.287	-

[a]Green time optimized by TRANSYT.

(Table 1), where NETSIM results indicated that the MAXBAND settings were slightly better in terms of stops and delay and TRANSYT results indicated that the TRANSYT settings were better in terms of PI (which is a weighted sum of stops and delay). This result has also been found by Rogness and Messer, as reported in a paper elsewhere in this Record.

3. The assertion that TRANSYT does not guarantee global optimum is amply demonstrated, especially on Hawthorne. Compare, for instance, experiments 2 and 3 (Table 1): Here, use of initial MAXBAND offsets in TRANSYT instead of the TRANSYT default starting timing plan resulted in a 15 percent improvement as indicated by NETSIM (using delay as a criterion) and a 10 percent improvement as indicated by TRANSYT (using PI as a criterion).

4. The improvements obtainable from optimizing phase sequence can be substantial, as seen for Hawthorne in Table 1. For instance, if experiments 1 and 9 are compared, MAXBAND settings with phase sequence optimization were 17 percent better in terms of delay than the MAXBAND settings without phase sequence optimization. In a comparison of experiments 2 and 10, an improvement of 7 percent in terms of delay for TRANSYT was achieved. If one compares experiments 2 and 11, combining MAXBAND offsets and phase sequence in TRANSYT resulted in a 20 percent improvement over TRANSYT with default offsets and no sequence optimization.

5. Improvements in TRANSYT-computed settings using MAXBAND starting offsets and all other optimization capabilities were quite good on Hawthorne and good on University. When experiments 2 and 14 for both arterials were compared, the following improvements were obtained: for Hawthorne, 23 percent reduction in delay, 12 percent reduction in stops, 5 percent improvement in fuel efficiency, and 27 percent reduction in TRANSYT PI; for University, 13 percent reduction in delay, 9 percent reduction in stops, 4 percent increase in fuel efficiency, and 10 percent reduction in TRANSYT PI. Thus, even though the incremental changes indicated by the earlier experiments were small (probably due to the lower demand levels on University), the additive effect of using all MAXBAND capabilities produced substantially better timing plans.

6. Improvements in MAXBAND settings achieved by using the green phase time optimization capability of TRANSYT were substantial on Hawthorne but quite small on University. In a comparison of experiments 12 and 16, the following improvements were obtained: (a) 9 percent reduction in delay, 16 percent reduction in stops, and 2 percent increase in fuel efficiency on Hawthorne and (b) 2 percent reduction in delay, no reduction in stops, and 0.5 percent increase in fuel efficiency on University.

CONCLUSIONS

From the results of this work, it can be concluded that using both the MAXBAND and TRANSYT programs in sequence to compute signal timing plans on arterials has a substantial potential for producing better signal timing than using either program alone. This is particularly true in cases where left-turn phasing on the arterial is used. There is also evidence that use of the TRANSYT traffic model as an evaluation tool is suspect in that it appears to underestimate the quality of bandwidth solutions.

RECOMMENDATIONS

For a practitioner who wishes to use both MAXBAND and TRANSYT, the following sequence of steps is recommended as being likely to provide near-optimum timing plans:

1. Using either volume and capacity information or existing green times, execute MAXBAND to provide offsets, cycle length, and phase sequence.
2. Using the results of step 1 as the input, execute TRANSYT to provide final offsets and green times.

This was the sequence of steps that was used to achieve the results in experiment 15.

REFERENCES

1. G.W. Schoene and G.W. Euler. Energy Conservation Through Traffic Signal Optimization. Presented at 51st Annual Meeting, ITE, Boston, MA, 1981.
2. C.E. Wallace and others. National Signal Timing Optimization Project: Final Evaluation Report. Office of Traffic Operations, FHWA, HTO-23, 1982.
3. P.B. Hunt and J.V. Kennedy. A Guide to TRANSYT/7. Transport and Road Research Laboratory, Crowthorne, Berkshire, England, Note UN78.11, 1978.
4. C.F. Wallace and others. TRANSYT 7F User's Manual. FHWA, HTO-23, 1983.
5. J.D.C. Little and others. MAXBAND: A Program for Setting Signals on Arterials and Triangular Networks. TRB, Transportation Research Record 795, 1981, pp. 40-46.
6. C.J. MacGowen and H.S. Lum. SIGOP or TRANSYT. ITE Journal, Vol. 45, No. 4, April 1975, pp. 46-50.
7. Traffic Network Analysis with NETSIM: A User's Guide. FHWA, HRT-20, 1980.

Publication of this paper sponsored by Committee on Traffic Signal Systems.