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Foreword

Traffic congestion remains a serious problem in many urban areas across the country. Where new lanes cannot be added because of physical or fiscal constraints or cannot be accomplished in the short term, alternative solutions must be found. These alternative solutions can include preferential lane treatments to encourage the use of high-occupancy vehicles (HOVs) and improved computer modeling of road networks to provide improvements in traffic signal systems. This Record contains papers in which such alternative solutions are discussed; the papers are sponsored by the Committee on Transportation System Management, the Committee on Parking and Terminals, and the Committee on Traffic Signal Systems.

In the initial group of papers, the utilization of preferential treatments for HOVs is discussed. In the first paper Wesemann describes how Orange County, California, used census data and a microcomputer-based estimation process to forecast the potential long-range use by buses and HOVs of exclusive roadway facilities. Ulberg and Jacobson analyze the cost-effectiveness of existing HOV lanes versus the alternatives of doing nothing or adding a lane for general traffic. Batz presents information on 19 specific HOV treatments and develops conclusions related to their effectiveness.

Lomax describes a procedure that can be utilized by agencies in urban areas to estimate the relative traffic congestion levels on urban roadway systems. Willson discusses the results of surveys of commuters in the Los Angeles area regarding the impact of parking subsidies on their transportation mode choice decision-making process.

The final group of three papers deals with the utilization of computer models for traffic signal optimization. Moskaluk and Parsonson discuss modification to the TRANSYT-7F optimization process to provide an increased priority to the main arterial traffic movements and controlled degradation to the minor movements and cross-street traffic. Chang et al. look at extensions to the MAXBAND program to allow it to provide phase sequence optimization in multiarterial closed networks. In the final paper, Yagar reports on a method of network formulation in TRANSYT-7F to provide more realistic results on networks where there is significant transit vehicle interference on the traveled roadway at signalized intersections.

Forecasting Use on Proposed High-Occupancy-Vehicle Facilities in Orange County, California

LARRY WESEMANN

Mobility problems being encountered in Orange County, California, are significant and are expected to become worse. In response, the Orange County Transit District is pursuing a transit development strategy that involves the provision of exclusive preferential facilities for buses and high-occupancy vehicles (HOVs). In developing this transitway program, a detailed analysis of potential long-range use was made, focusing on the emerging major activity centers in Orange County. The required HOV and transit demand estimates were developed through a microcomputer-based estimation process that involved nine specific tasks; a spreadsheet program was used along with various BASIC programs. Journey-to-work travel data for 1980 from the Census Bureau Urban Transportation Planning Package were used as a base and expanded to the year 2010 by using adopted population and employment growth factors. Mode splits were determined on the basis of the degree of travel-time savings that trips would achieve by using the preferential facilities in the a.m. peak hour versus mixed-flow freeways as well as origin and destination characteristics. The degree of increase in mode-split values for transit and HOVs was largely a function of corridor statistical trends from studies of before-and-after conditions on other priority projects nationwide. HOV trips were assigned by microcomputer to a network of preferential facilities using equations that specified the ranges of cells from the trip matrix that would pass through links in the network. The equations were applied to a master file of projected HOV trips to produce directional link and access-egress volumes.

In this paper the travel-forecasting approach is described that was employed by the Orange County Transit District (OCTD) to provide bus and high-occupancy-vehicle (HOV) use estimates necessary for OCTD's Transitway Concept Design Study, the primary planning phase of the Transitway Development Program for Orange County, California. The application selected is highly specialized and was developed and performed by staff using available microcomputer hardware and software. The approach is a product-driven process that focused on meeting the demand requirements necessary to conduct concept design work at the expense of answering broader intermodal travel-forecasting questions.

REQUIREMENTS FOR A DIFFERENT APPROACH TO TRAVEL FORECASTING

In 1985, OCTD made a decision to develop its own approach to travel forecasting that focused solely on meeting the demand requirements necessary to conduct the Transitway Concept Design Study. The forecasting approach selected is radically different from the traditional Urban Transportation Planning System (UTPS) process and is highly flexible, has easily tracked input and output, and can be performed on available microcomputer hardware and software. The development of this process was governed by the requirements discussed in the following sections.

Shifting Program Emphasis

A need had been identified for a different travel-forecasting approach to meet the complex planning requirements of OCTD's new transitway program emphasis. The UTPS aggregate model chain provided output that was suitable for previous rail project analysis. However, the new emphasis on preferential facilities required that HOV as well as conventional transit demand be more thoroughly analyzed.

Lack of Proven HOV Travel Model in Los Angeles Region for Transitway Study

No conventional travel model being used within the region in 1985 was capable of replicating behavior shifts to rideshare modes in response to newly available exclusive facilities and changing corridor characteristics. In addition, no regional agencies had developed packages for assigning HOV trips to a separate network of exclusive facilities.

Flexibility and Tracking Ability

A need existed for maximum flexibility in developing forecast output for Transitway Concept Design Study tasks and easily tracked input and output. As work progressed

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on the study, OCTD staff needed to respond to emerging planning and design issues that affected facility capacity, operations, and access features. A forecasting tool was needed that would allow for ease in modifying input assumptions and variables and would facilitate a quick analysis of the effects of these changes on output.

Comparison Capability

A need existed for the ability to compare travel-forecasting input and output with data from HOV model development and field work being done by other agencies in the Los Angeles region.

Spatial Requirements

A need existed to develop detailed estimates for site-specific analysis, such as that for an access ramp, as well as a corridorwide focus. Several rapidly growing employment centers in Orange County required a more detailed analysis of demand from exclusive facilities in the a.m. peak period.

Limited OCTD Travel-Forecasting Resources

On a short-range basis for initial concept design tasks, OCTD needed to develop an estimation approach that could use available in-house microcomputer resources and staff expertise. At the same time, it was decided to begin an evaluation study of long-range travel-forecasting needs, eventually allowing the agency to perform more sophisticated travel-forecasting activities.

STUDY OVERVIEW

By 2010, Orange County's population is projected to have grown by 45 percent to more than 2.8 million, jobs by nearly 65 percent to nearly 1.6 million, and daily trips by nearly 90 percent to 13 million. The mobility problems currently being encountered by Orange County residents will become worse as the growth occurs. As previous studies have shown, these problems have a magnitude and complexity that cannot be solved entirely by the building of more streets and highways. Clearly, a multimodal solution is needed. One such approach, successful in Southern California, involves the implementation of bus-HOV facilities within freeway rights-of-way (e.g., the El Monte Busway in Los Angeles County along I-10). This preferential treatment provides travel-time savings to those willing to share a ride. Eligible users include public transit, private buspools, vanpools, and carpools.

Planning Approach

The planning for the transitway development program for Orange County involved an intensive analysis of the major activity centers in Orange County and the need to serve these centers through a higher level of transportation service than can be provided by today's transportation system. The analysis focused on the relationship of a transitway system to the major activity centers, transitway demand estimates for both buses and carpools for the year 2010, and the benefits that are likely to accrue from use of transitways. As shown in Figure 1, the proposed 19.4-mi system of limited-access transitways is directly adjacent to most of the county's activity centers and provides an interface with current and proposed commuter (carpool) lanes.

Location and Size of Activity Centers

The eight activity centers that are within the central core of Orange County are shown in Figure 1. All of the centers are within 1 mi of freeway corridors, and workers at these centers are heavily dependent on these freeways for access to their jobs.

Forecasts of jobs for each center were made on the basis of adopted plans. The eight centers currently have a combined total of approximately 245,000 jobs. Employment in these centers is projected to increase to a cumulative total of nearly 350,000 jobs by 2010, a 43 percent increase. These forecasts served as a basis for projecting use of the proposed barrier-separated transitways.

The existing employment and the growth planned over the next 15 to 25 years highlight the need for a more efficient use of the transportation system. This growth further reinforces the need for the development of a program of preferential facilities to move large numbers of people more effectively.

DEMAND ESTIMATION APPROACH

Methodology

The selection of a travel estimation approach for projecting HOV and transit use on exclusive facilities was based on fulfilling specified output requirements constrained by a limited time frame and available in-house forecasting resources. The approach selected for estimating demand for transitways and commuter lanes was called the Urban Transportation Planning Package (UTPP) Base/Socio-economic Growth Approach. The process involved nine specific tasks, which are described in the following section, and the analysis was conducted on an IBM XT personal computer using a spreadsheet software program along with various BASIC programs developed by the staff.

The 1980 U.S. census journey-to-work travel data from the UTPP formed the base data set for producing year 2000 and 2010 projections of facility use. The base-year person-trip data were built up to forecast-year trip totals by using an iterative distribution application that was constrained by the adopted Orange County growth forecasts for origin and destination areas. This iterative approach

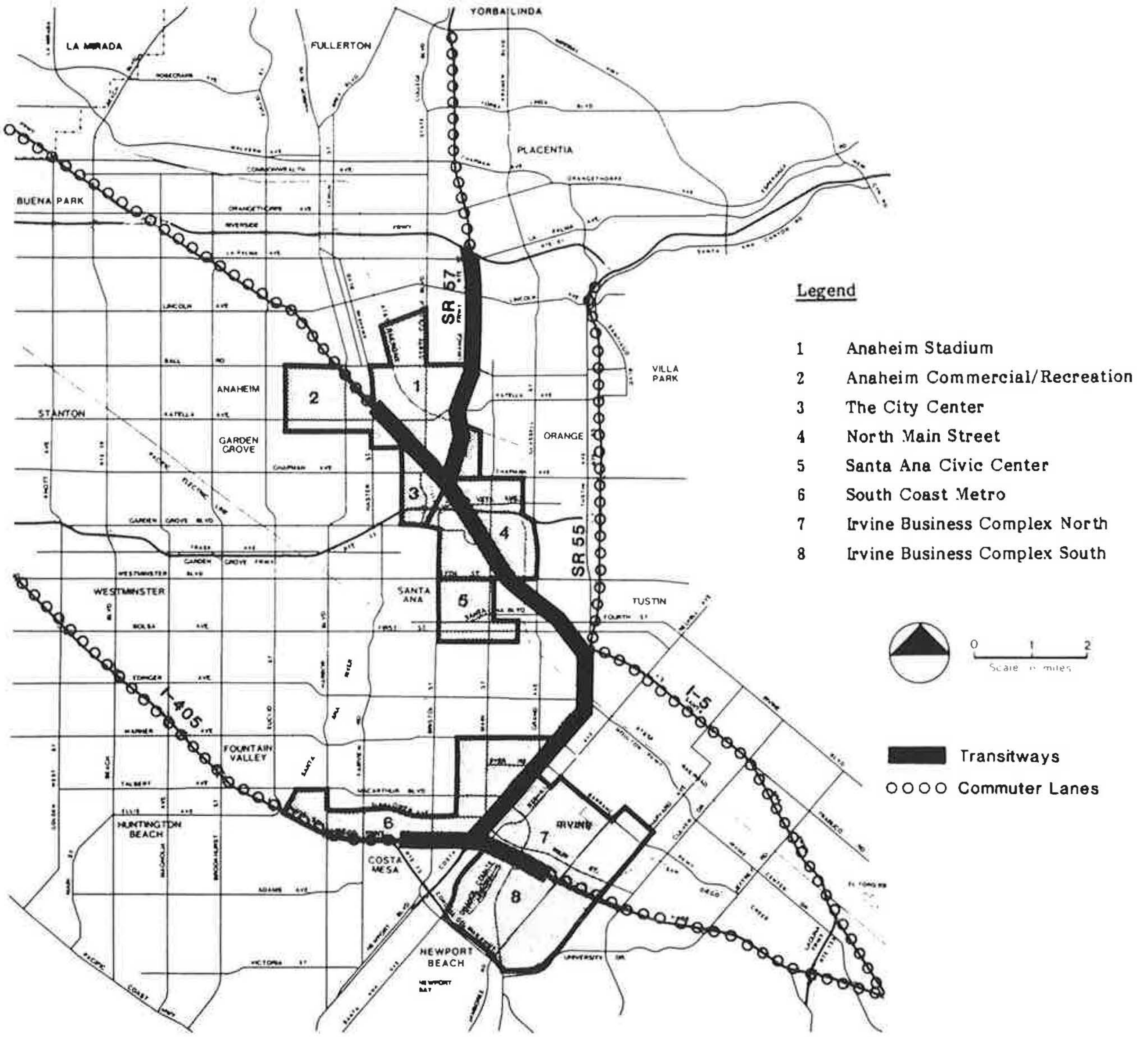

FIGURE 1 Relationship of transitway system and activity centers.

used the trip distribution from the UTPP data base as a platform on which to expand the journey-to-work trip table to levels more representative of the forecast years.

Transit and HOV mode splits were primarily determined on the basis of the degree of travel-time savings that commute trips would achieve by using preferential facilities rather than mixed-flow freeway lanes in the a.m. peak hour along with origin and destination area characteristics. (From the employee survey results in the 1986 Commuter Network Evaluation Study conducted by OCTD, travel-time savings was identified as the principal incentive that would encourage Orange County commuters to rideshare.) The degree of increase in mode-split values for transit and HOVs was established on the basis of changes in facility and corridor modal statistical trends from before-and-after studies related to the opening of other HOV priority projects nationwide. [Transitway Concept Design Working Paper B-2: Operations Plan (*1*) contains a detailed analysis of facility and corridorwide statistics on modal shift from before-and-after studies related to the opening of preferential projects around the country.]

Demand Estimation Process

The demand estimation process involved nine specific tasks, some of which contained numerous steps. Figure 2 shows the sequence of tasks along with key input and output.

Task 1: Review System-Level Demand Analysis Assumptions, Process, and Output

An HOV estimation process from a previous OCTD system-level analysis of preferential facilities was reviewed,

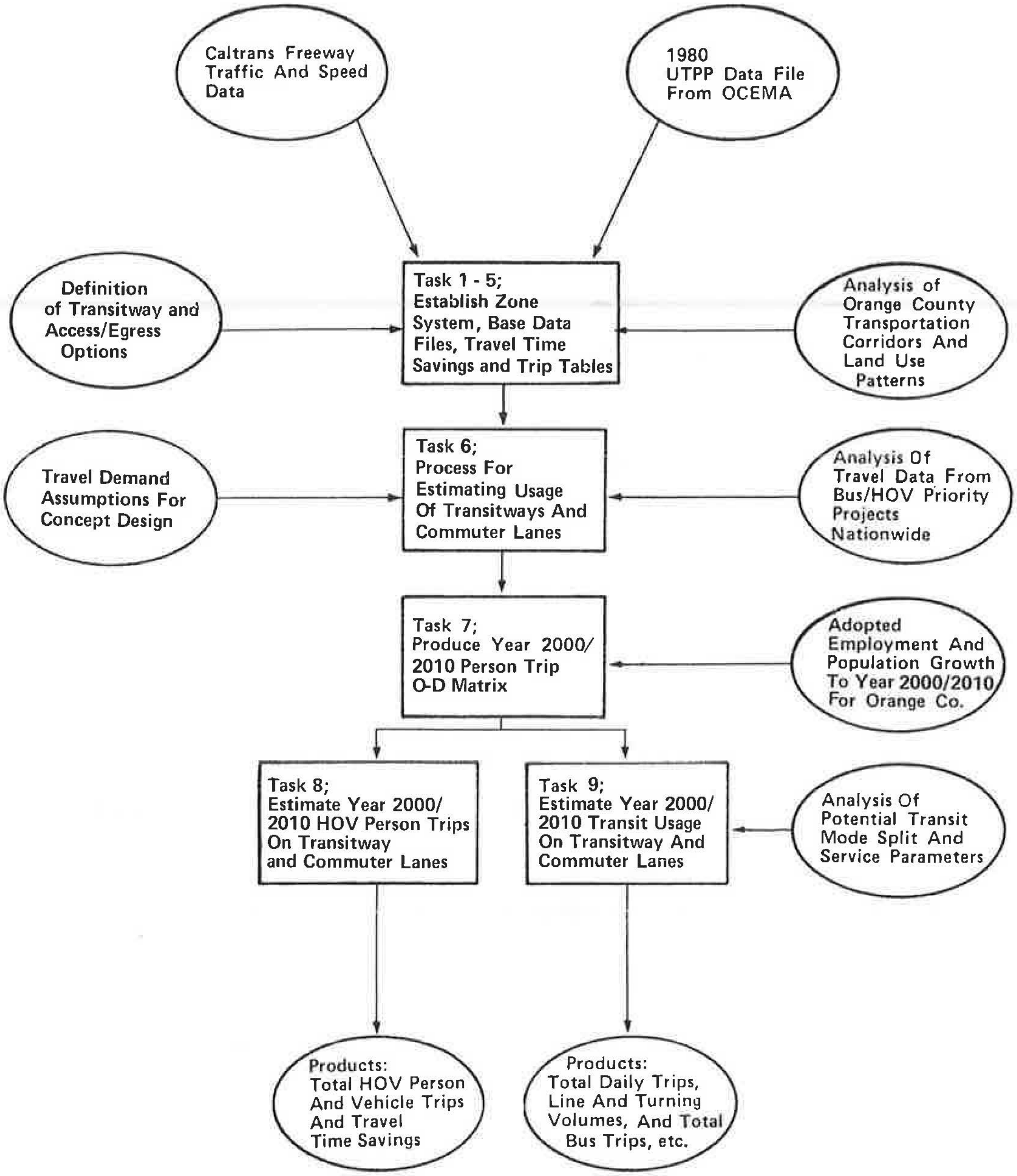

FIGURE 2 Process for estimating transit and HOV use on transitways.

and changes were made as required to, among other things, the zone system, speed assumptions, prior mode assumptions, and transit and HOV mode-split factors.

Task 2: Establish Zone Systems and Design Origin-Destination Matrix for Microcomputer Analysis

The Transitway Concept Design Study zone system was designed to be more detailed to allow for a more concentrated analysis of access and egress along specific travel corridors in the study area. A 54-zone system was established for the study, and an origin-destination (O-D) matrix was designed.

Task 3: Establish Base Data Files and Determine Background Assumptions

The 1980 UTPP data files for total person-trips, two-person carpools, and three-person carpools were aggregated to the zone system, and specific background assumptions were established using travel behavior information from nationwide studies of preferential facility projects along with freeway data from the California Department of Transportation (Caltrans), HOV counts, and vehicle occupancy data.

Task 4: Estimate Travel-Time Savings on Transitway Versus Freeway for All Trip Interchanges

Existing Caltrans peak-hour speed and congestion data were compared with free-flow speeds assumed for preferential facilities to determine the amount of line-haul travel-time savings that would be assigned to each O-D cell in the matrix. Travel-time savings estimates were computed on the basis of the higher speeds that commuters would achieve on preferential facilities within individual corridor segments as well as through major freeway interchanges via high-speed ramps and on exclusive access ramps into activity centers.

Task 5: Delete O-D Cells with Short Trip Lengths and Produce 1980 Trip Tables

Because of the difficulty in weaving across congested freeway lanes both into and out of commuter lanes and the infrequency of controlled transitway access and egress ramps, few commute trips of less than 7 mi would gain from using these preferential facilities. Therefore, all short trips, along with trips made in areas of the county not served by preferential facilities, were deleted from the matrix. (Commute trips of less than 7 mi combined with trips outside the scope of the study constituted approximately 53 percent of all 1980 journey-to-work trips within Orange County, according to the UTPP data.)

Task 6: Estimate HOV Person-Trips on Transitways and Commuter Lanes

First, each O-D cell in the matrix was categorized by the amount of line-haul travel-time savings attributable to each cell's travel path on the preferential facilities versus that on mixed-flow freeways. O-D trip cells with less than 5 min of travel-time savings were not added to the trip table for preferential facilities because this level of savings was not considered sufficient to cause commuters to switch from freeway lanes. Varying portions of the trip totals for all other O-D pairs were added to the appropriate category of travel-time savings in the transitway trip table within which they fell (see Table 1).

Next, HOV trips in the transitway trip tables were increased by the degree of travel-time savings to account for the influence of the benefits of the transitway on propensities to form carpools. Finally, all HOV person-trip totals were reduced by 10 percent to account for a daily travel factor (vacations, sick time, etc.), and an additional 20 percent more trips was added to account for nonwork HOV travel on the preferential facilities in the a.m. peak period.

TABLE 1 FACTORS USED IN ESTIMATING HOV PERSON-TRIP USE FOR TRANSITWAYS AND COMMUTER LANES

Category of Travel-Time Savings	Percentage of Existing Trips Shifting to Transitways		Percentage of Increase in HOV Formation for Trips Using Transitways
	Trips 7 mi or Less	Trips > 7 mi	
< 5 min	No shift	No shift	No increase
5–9 min	No shift	65–75	20–30
10–14 min	No shift	75–85	30–40
15 min or greater	No shift	85–95	40–50

(Data in this section are derived from the 1984 Caltrans survey of HOV users on the El Monte Busway in Los Angeles during peak periods.)

Task 7: Produce Person-Trip Tables for 2000–2010

Years 2000 and 2010 were selected as projection years for OCTD's Transitway Concept Design. Year 2000 represents a design year for the transitway and 2010 is the horizon year for the demand analysis. The production of future years' trips was accomplished by increasing the base-year 1980 UTPP person-trip table by adopted socioeconomic growth factors for Orange County [Orange County Preferred-1985 (OCP-85) Projections prepared by the Forecast and Analysis Center of the Orange County Administrative Office]. Origin zonal trip totals were increased on the basis of population and destination zonal trip totals by employment. An iterative approach was used to build from the 1980 trip distribution that existed in the UTPP data base to a future-year distribution. Trip imbalances between origins and destinations were eliminated by reallocating trips from cells with trip excesses to cells with trip deficiencies. This task was accomplished on an IBM XT personal computer with a software program developed by staff and written in BASIC. This quick-response procedure for projecting a future-year person-trip table in an O-D format produced output that was used on Lotus 1-2-3 spreadsheets to perform the estimation of future-year HOV person-trips using mode splits derived in Task 6.

Task 8: Estimate and Assign HOV Person-Trips on Transitways for 2000–2010

HOV trip totals were assigned to transitway links using a microcomputer assignment application developed by staff. The software application contained a series of equations that specified the ranges of O-D trip cells from the trip matrix that were assumed to pass through each directional link in the transitway network. One equation of O-D ranges was specified for each directional transitway link. The equations were applied to a master file of projected HOV vehicle trips using a Lotus 1-2-3 spreadsheet to produce directional link volumes and ramp counts for the a.m. peak hour.

Task 9: Estimate Transit Use on Transitway for 2000–2010

Transit use on preferential facilities was estimated for future years. Origin market areas and destinations that can be collectively served by transit were identified in the estimation matrix. The largest of these, along with individual O-D cells of 300 person-trips or more, were selected from the 2010 trip table as having transit potential. Next, a range of transit mode splits was developed based on the degree of travel-time savings and origin and destination characteristics, along with trip distance and level of service. These mode splits were applied to appropriate O-D pairs in the table of person-trips with transit potential to produce a transit trip table. The transit trip cell totals were then categorized by size; those in excess of 150 peak-period trips were assigned to express bus routes. Totals under 150 were assumed to be too low to justify express bus service. Express bus use totals were increased by 7 percent to account for nonwork trips carried during the peak period. (Data in this section are based on output from the 1979 and 1982 OCTD on-board surveys and the 1984 Caltrans survey of transit riders on SCRTD routes using the El Monte Busway.)

Key Assumptions Used in the Demand Estimation Process

Three categories of assumptions were made in the demand estimation work: general (e.g., travel growth, operating speeds), HOV (e.g., person-trips assigned to facilities, increase in formation), and transit (e.g., market requirements, mode splits) (Table 2).

Of particular note in the demand estimation process is the step-by-step build-up approach used. Beginning with existing HOV person-trips (1980 UTPP data file), each step of the process allows for two important activities to occur:

1. Trip tracking: O-D pair trips can be tracked throughout the entire HOV demand estimation process. This allows the forecaster to assess the validity of every step in the forecasting process.
2. Changing assumptions: In the event that different data exist, any of the assumptions can be altered and the process redone.

In combination, these two facets of the estimating process allow the forecaster to communicate clearly to the technical community precisely how the HOV and transit link volumes and facility access-egress estimates were derived.

Data Base for 1980

Table 3 (*2*) contains a summary of the 1980 UTPP journey-to-work data base that formed the basis for this demand analysis. Of the nearly 1 million journey-to-work person-trips in the data base (internal Orange County trips plus those of external origin), only 507,243 were included in this analysis because of the exclusion of trips shorter than 7 mi and trips that occurred in areas and directions not served by either transitways or commuter (carpool) lanes.

In this analysis 95,792 journey-to-work person-trips listed as being in HOVs of two persons or more are included, which constitutes nearly 19 percent of the total of 507,243. The remaining 79,475 journey-to-work carpool person-trips were dropped from the analysis because of short trip lengths or trip directions not served by the proposed preferential facilities.

Congestion Assumptions and Travel-Time Saving

At least four factors were assumed to contribute to the attractiveness of transitways and carpool lanes to commuters in Orange County: improvements in travel reliability (more on-time arrivals), a better traveling environment (increased freedom from congestion and incidents), improved safety (protection because of barrier separation), and shortened travel time during peak commute hours. Of these benefits, shortened travel time is the most quantifiable in terms of its impacts on user behavior. Therefore, it was the principal variable used in this analysis to govern increases in carpool formation rates within travel corridors.

Travel-time savings affected two steps of the demand estimation process under Task 6: mode choice and the assignment of HOVs to the transitway. For these two steps, travel-time savings was interpreted as the number of minutes that could be saved if commuters would use exclusive transitways for the line-haul portions of their trip, including use of the special direct-egress ramps to activity centers. These travel-time savings were calculated for a.m. peak-hour travel on transitways versus congested mixed-flow freeways.

Travel-time savings affected the assignment of HOV person-trips to transitways in two ways. First, a minimum travel-time savings of 5 min was used as a low end point for assigning trips to transitways. Second, three categories of line-haul travel-time savings (5 to 9 min, 10 to 14 min, and 15 min or more) were used to assign percentages of HOV person-trips to transitways.

Travel-time savings were also used to determine mode choice for HOVs and express transit using transitways. For HOV person-trips, the degree of increased carpool formation that was applied to O-D trip cells was determined by which of the three categories of travel-time savings applied. For express bus, the degree of travel-time savings directly affected the percentage of total journey-to-work person-trips that transit attracted from each trip cell in the O-D matrix.

TABLE 2 ASSUMPTIONS USED IN THE HOV AND TRANSIT ESTIMATION PROCESS

CATEGORY	ITEM	ASSUMPTION
GENERAL	Travel Growth	1980 to 2000: 45% increase in travel. 1980 to 2010: 62% increase in travel.
	Travel Distribution	1980 UTPP distribution used for 2000 and 2010 except for employment centers not existing in 1980.
	Operating Speeds	General freeway: 1983 peak period speeds. Transitway & Commuter Lanes: 55 mph on mainlines. Transitway Ramps: 20-45 mph, depending on geometrics.
	Travel Time Savings for Transitways and Commuter Lanes	Mainlines: Based on speed difference (1983 existing and 55 mph). Access/Egress Ramps: 1-5 minutes.
HOV	Base Person Trip File	All 1980 HOV person trips from UTPP with travel distances greater than 7 miles and travel paths containing transitways or commuter lanes.
	HOV Person Trips Assigned to Transitways and Commuter Lanes	65% - 95% of O-D pairs in trip file, depending on travel time savings (refer to Table 1).
	HOV Formation	Increase of 20% - 50% of assigned trips depending on travel time savings (refer to Table 1).
	Non-Work Trips	Increase of 20%
	HOV Occupancy	With 2+ Restriction: 2.50 persons/vehicle With 3+ Restriction: 3.50 persons/vehicle
	3+ HOV Growth	Increase of 30%-50% from 1980 UTPP (Note: Base person trip file reflected 25% of HOV person trips were in 3+ vehicles).
TRANSIT	Base Data File	Base Person Trip File (HOV), with O-D cells of greater than 150 person trips.
	Transmit Mode Split	3% - 15% depending on travel time savings, level of transit service, origin/destination zonal characteristics.
	Prior Mode	15% - 25% of new transit users were formerly carpoolers. Carpool person trips reduced accordingly.

VALIDATION OF HOV DEMAND ESTIMATION APPROACH

A validation check was performed on output from the HOV demand estimation approach using available ground counts of HOVs before and after commuter lanes were opened on Route 55 in Orange County. Table 4 contains a comparison of UTPP travel demand estimates for 1980 and 1985 with carpool volumes observed by Caltrans before and after the opening of the Route 55 commuter lane project (*3*). Two southbound cut lines (Walnut Street 90 days after opening and Santa Clara Street 6 months after opening) are compared after the carpool lanes opened with corresponding links from the demand analysis network.

Three aspects of the HOV demand estimation approach were validated against observed data on Route 55: the percentage of carpools shifting to the commuter lane versus that remaining on the freeway, commuter lane use in the a.m. peak period, and the growth in HOVs within the corridor resulting from the opening of the preferential facilities. In addition, the vehicle occupancy assumptions used in the HOV estimation approach were compared with observed occupancies for vehicles using the commuter lane, excluding violators.

As shown in Table 4, Caltrans observations indicate that approximately two-thirds of the 730 to 770 carpools observed on the Route 55 freeway before the opening of the commuter lane (62 percent at Walnut Street for 90 days after opening and 69 percent at Santa Clara Street for 6 months after opening) shifted from the freeway to the commuter lane. The remaining one-third of the observed preproject carpools, 290 at Walnut and 230 at Santa Clara, remained in mixed-flow traffic on the freeway lanes. These carpools either were in the process of weaving in or out of the commuter lane at the point of observation or were not using the commuter lane because of a short trip length.

The range of 62 to 69 percent of existing HOVs shifting to the commuter lane found in the field observations on

TABLE 3 SUMMARY OF 1980 DATA BASE

1980 SOCIO-ECONOMIC SUMMARY FOR ORANGE COUNTY[1]

Total Population = 1,932,709
Total Households = 687,059
Average Household Size = 2.81
Workers at Residence = 974,845
Workers/Household = 1.42
Workers/Population = 0.50
Workers at Place of work = 889,546
SCAG-82 Growth Forecast = 940,100

UTPP JOURNEY TO WORK TRAVEL CHARACTERISTICS[1]

Total Workers by Area of Origin = 899,457
Breakdowns by Mode:

Drive Alone = 725,829 (80.69%)
2 Persons/vehicle = 116,649 (12.97%)
3+ Persons/vehicle = 38,157 (4.24%)
Total Carpool Persons Trips = 154,806 (17.21%)
Transit = 18,912 (2.10%)

Countywide Average Auto Occupancy = 1.130

MODAL SHARES OF TRIPS IN ORANGE COUNTY

Source	Type of Trip Surveyed	Year	Drive Alone %	Carpool Occupant %	Bus %	Other %
US Census Special Survey[2]	Work	1977	79	16	2	3
US Census Decenniel Census[2]	Work	1980	75	16	2	7
SATC Model[3] Estimate Home Based Work	1980	81.2	16.4	2.4	-	
Other		47.0	52.0	1.0	-	
1980 UTPP[1] Data File Work	1980	81.7	17.2	2.1	-	

Sources: 1. 1980 U.S. Census - Urban Transportation Planning Package (UTPP) Data File.

2. Selected Characteristics of Travel to Work in 20 Metropolitan Areas: 1977, U.S. Bureau of the Census, U.S. Department of Commerce, January 1981.

3. Santa Ana Transportation Corridor Transit Element Alternatives Analysis (Stage II), Orange County Transit District, February 1984.

Route 55 is somewhat lower than the range of 70 to 75 percent carpool shift used in the HOV estimation approach for transitway network Links 79 and 81. However, this difference is attributable to the fact that short HOV trips of 7 mi or less are included in the observed data but were eliminated from the forecast data set.

In Table 4 observed Route 55 commuter-lane use for 90 days and for 6 months after the November 1985 opening is also compared with use derived through the HOV estimation approach for 1980 and 1985. Two-person-plus HOV volume observed southbound at Walnut Street 90 days after opening was approximately 1,100 vehicles in the a.m. peak hour, whereas HOV volume at Santa Clara Street was 1,178 six months after the opening of the Route 55 commuter lanes. This compared favorably with the projected 1985 HOV volume of 1,266 vehicles in the a.m. peak hour southbound on Link 79 and 1,114 vehicles on Link 81.

The use estimates for the 3-hr a.m. peak period derived through the HOV demand estimation approach also closely paralleled observed use on the commuter lane. The approach yielded 3-hr a.m. peak-period HOV person-trip totals for 1985 of 7,124 for Link 79 and 6,268 for Link 81 southbound. Caltrans observations indicated that approximately 6,150 persons used the southbound commuter lane 90 days after opening during the 3-hr a.m. peak.

The comparison of the derived with the observed percentage increases in a.m. peak-hour carpools for the Route 55 corridor after the opening of the commuter lane indicated that the output from the estimation approach may

TABLE 4 COMPARISON OF HOV TRAVEL DEMAND ESTIMATES WITH OBSERVED 2+ CARPOOL VOLUMES ON ROUTE 55

	CARPOOL VOLUMES OBSERVED BY CALTRANS		UTPP BASE/SOCIO-ECONOMIC GROWTH TRAVEL FORECASTING APPROACH			
	1984 THROUGH 1986		1980 BASE YEAR DATA		1985 ESTIMATE[5]	
	Southbound AM Peak:		**Southbound AM Peak:**		**Southbound AM Peak:**	
	Walnut St.	Santa Clara St.	LINK 79	LINK 81	LINK 79	LINK 81
	Before Lanes Opened[1]		**UTPP Input Data**			
o **1984/85 AM Peak Hour HOV Vehicle Trips Before Commuter Lanes Opened**	770	730	879	734	967	807
	After Lanes Opened		**After Trip Assignment**			
	90 days	**6 months**				
Remained In Mixed Flow Lanes[2]	290 38%	230 31%	264 30%	184 25%	290 30%	202 25%
Switched to Commuter Lane	480 62%	500 69%	615 70%	550 75%	677 70%	605 75%
o **Commuter Lane Statistics**						
- Peak Hour Vehicles	1100	1178	1151	1013	1266	1114
- 3 Hour AM Peak Period						
o Vehicles	3000	3097	2878	2532	3166	2785
o Persons	6150	6250	6476	5698	7124	6268
o Occupancy[3]	2.05	2.02	2.25	2.25	2.25	2.25
o **Total Peak Hour Carpools Southbound In SR 55 Corridor**	1390	1408	1415	1197	1556	1316
o **Percent Increase In Corridor Carpools After Opening**						
- Southbound AM	81%	93%	61%	63%	61%	63%
- Northbound PM	60%	65%	65%	67%	65%	67%
- Composite[4]	70%	78%	63%	65%	63%	65%

[1] Average of three observation days 4/84, 11/84, 10/85.

[2] Derived from observations by Caltrans 90 days and 6 months after the commuter lane opened. Occupancy for freeway lanes between 1.07 to 1.09 persons per vehicle.

[3] Observed average at Meats and Santa Clara Streets southbound on the SR 55 Commuter Lanes.

[4] Average of northbound PM peak and southbound AM peak.

[5] Assumes 10 percent growth in SR 55 corridor between 1980 and 1985.

Source: Route 55 Commuter Lane Demonstration Project 90 Day Evaluation Report, and Six Month Status Report, Caltrans, February 1986 and June 1986

be understating actual growth. The 70 percent composite growth in Route 55 corridor carpools observed 90 days after opening has already surpassed the 63 to 65 percent composite southbound a.m. and northbound p.m. growth produced from the HOV estimation approach. The number of a.m. peak-hour carpools observed 6 months after the opening of the commuter lane had grown to 78 percent higher than preproject levels.

Some caution must be used in validating the HOV estimation approach with the Route 55 commuter lane project. The phenomenal growth in carpools over such a short period of time in the Route 55 corridor is believed to have been caused by many conditions, some of which may not exist in other freeway corridors in Orange County. First, some of the growth may merely be due to the switching of facilities by existing carpools. Route 57 is a heavily congested parallel freeway with no commuter lanes, so it is likely that some of its HOV trips changed to the Route 55 commuter lane after it became operational.

Second, Route 55 serves many long-distance intercounty commute trips that may be more likely to lead to formation of carpools than the somewhat shorter internal Orange County trips. Finally, Caltrans considers Route 55 an undersized freeway facility that has prolonged periods of congestion in both the morning and the evening. This may also stimulate rapid growth in carpool formation because commuters have no other way to avoid congestion, such as shifting their commute trip to an earlier or later time to avoid the heaviest traffic.

DEMAND ESTIMATES AND ANALYSIS RESULTS

Under eligibility rules that allow two-person-plus HOVs, the transitway is projected to carry 55,445 to 68,185 peak-period person-trips in 2010. If the transitway were restricted to three-person-plus HOVs, it would carry 21,160 to 30,695 peak-period person-trips in 2010. On the basis of these projections and the two-person versus three-person-plus modal splits contained in the 1980 UTPP data file, over one-half of the HOV person-trips and nearly two-thirds of the HOV vehicle trips would be removed from the transitway if facility eligibility were increased from two-plus to three-plus persons in vehicles.

In Table 5 the projected 2010 combined three-person-plus HOV and transit volumes for Orange County transitways are compared with existing use from projects nationwide. Included in Table 5 are estimates of both vehicle

TABLE 5 PROJECTED 2010 ORANGE COUNTY TRANSITWAY VOLUMES COMPARED WITH VOLUMES ON EXISTING EXCLUSIVE FACILITIES

LOCATION	A.M. PEAK HOUR, PEAK DIRECTION VOLUME PER LANE	
	VEHICLES	PERSONS
Year 2010 Orange County (3+ carpool)		
Rte. 57 at Katella	950	4,950
I-5 at 17th Street	1,500	6,300
I-5 at 1st Street	1,600	7,000
Rte. 55 at Grand	1,450	6,500
Existing Projects		
El Monte; Los Angeles (3+)	1,100	6,500
Shirley; Washington D.C. (4+)	1,100	7,200
I-66; Washington, D.C. (3+)	1,500	6,000
Lincoln Tunnel; New York City (buses)	680	27,000
North; Houston (6+)	260	4,500
Rte. 55; Orange County (2+)	1,250	2,800
I-95; Miami (2+)	1,300	2,600
RANGE	260-1,500	2,600-27,000

and person-trips for the a.m. peak hour in the peak direction per lane. Estimated Orange County person-trip demand for 2010 is similar in magnitude to the existing use on the El Monte Busway in Los Angeles and the Shirley Highway in Washington, D.C. However, projected Orange County vehicle volumes are much higher—1,600 per hour versus 1,100 per hour for both of these existing facilities—indicating a higher proportion of carpools over buses. The express bus service on the Orange County transitways is projected to carry 11,100 peak-period trips in 2010 as compared with between 22,000 and 30,700 persons in carpools.

EVALUATION OF HOV DEMAND ESTIMATION APPROACH AND CONCLUSIONS

The HOV demand estimation approach developed by OCTD for use in transitway concept design is a highly specialized application that was developed solely for the purpose of providing necessary output on the use of exclusive HOV facilities to assist in facility design decisions. Certainly this narrowly focused approach has many limitations if looked at from a broader travel-forecasting perspective. However, the advantages inherent in this approach have made it an extremely useful tool for forecasting HOV demand in Orange County and deserve some further consideration as OCTD's travel demand capabilities are upgraded in the near future.

Evaluation of Estimation Approach

Advantages

The strengths of the HOV demand estimation approach and its application in Orange County can be analyzed under four separate categories: analysis capabilities, usefulness of output, cost and start-up requirements, and operational performance.

Analysis Capabilities The analysis capabilities that the HOV estimation approach provides for the user are quite significant, primarily because of the flexibility inherent in the process. The user has the ability to fully track progress through the chain of steps and observe the effects of changing input variables and assumptions. The UTPS model chain is very costly and time consuming to use, and it is often impossible to conduct analyses at intermediate steps in the model process. Furthermore, trips cannot be tracked through the UTPS model chain and thus the impacts of various model assumptions cannot be assessed.

Operational Performance The operational performance of the HOV estimation approach is excellent from the standpoint of being able to add, modify, and delete assumptions as the need dictates. The ease in modifying input is very important in Southern California because new information on HOV use characteristics is being made available from the data-gathering and field survey efforts being conducted by OCTD and Caltrans, among others. New regional data on activity-center-based and corridorwide HOV use and before-and-after statistics from exclusive HOV facility projects provide needed base information for model validation and adjustments to input assumptions.

The great flexibility inherent in the HOV demand estimation approach is due primarily to the division of the process into several distinct steps that can be easily isolated and worked with independently. The individual assumptions and variables of each separate step can be readily modified and reapplied to the process because of the record-keeping and tracking functions. Virtually the entire process is performed on data bases that are retained in an O-D format on a spreadsheet program. Therefore, it is relatively easy to operate by in-house staff who have a rudimentary understanding of microcomputer spreadsheet programs.

Usefulness of Output The usefulness of the output produced from the HOV estimation approach can be measured in terms of its level of detail and convertibility. The ease of operation and tracking abilities inherent in the process allow users to adapt the approach to several levels of spatial analysis. Because the primary input travel data base was the 1980 U.S. census journey-to-work trip table, base-year information was available at the census-tract level. This level of detail allows users to perform site analyses of corridor demand in specific destination areas to determine whether individual access features are required from transitways to arterials in activity centers.

Another strength of the output from this approach was the relationship of travel data to activity-center growth. The iterative trip build-up procedure that was used to produce the future-year person-trip table had a trip-balancing function that targeted growth in trips to specific adopted employment and population growth forecasts. This ensured that the rapidly growing activity centers of Orange County would not have deficiencies in home-based-work trip attractions, which has been the case with some output from past UTPS modeling applications in Orange County.

Cost and Start-Up Requirements The HOV demand estimation approach affords some real advantages in terms of cost and start-up requirements. OCTD was able to use existing hardware and software with some fundamental training of staff. The estimation can be performed on an IBM XT with BASIC and spreadsheet programs. In addition to low capital cost, operating costs are relatively minor, except for certain data-base manipulations that require staff time.

Required start-up time is not major in comparison with the months that are required to calibrate and operate a full application of the UTPS model. Because the HOV estimation approach is a specialized and relatively straightforward application, staff was not burdened with all the complexities of UTPS model calibration, testing, and verification.

Limitations

The HOV demand estimation approach used by OCTD in transitway concept design is a highly specialized demand application that does not provide the ability to deal with broader travel-forecasting issues, particularly for nonwork trip purposes and non-HOV travel modes. In this approach, the user is not able to conduct a complete analysis of intermodal travel relationships because no comparable output of freeway demand is produced. In general, the following limitations should be noted by potential users of this estimation approach:

- The approach is tied to the 1980 U.S. census journey-to-work travel data base. OCTD had to make gross assumptions about nonwork HOV trip purposes in conducting its analysis. Although work trips compose the major trip purpose within the a.m. peak period, other trip purposes have a major impact on facilities in the vicinity of existing and emerging multipurpose activity centers in Orange County.
- The approach to analyzing modal shift may be criticized as overly simplistic because the analysis focuses solely on travel-time savings. Although travel-time savings has been identified through field research as the major influence on commuter travel behavior in Orange County, it is by no means the only variable that affects trip making. Travel costs, income levels, system reliability, and safety considerations are all important influences on travel behavior and modal shift.
- There is no ability to perform a full analysis of corridorwide travel relationships because output is limited to HOV and transit use on exclusive facilities. The approach is not directly tied to any full-scale travel-forecasting effort that has a highway network and an assignment of trips to a system of freeways and surface arterials.
- The approach does not specifically include a trip distribution phase but merely uses trip making that is inherent in the base-year conditions. An analysis of trip making would normally be an integral function of a travel-forecasting process, and future applications of this approach would need upgrading in this respect.

Deficiencies of Current HOV Models

A major deficiency in HOV behavioral data nationwide is the change in HOV vehicle occupancy related to changes in occupancy restrictions on exclusive facilities. The growth in three-person-plus HOV travel over time due to changing facility restrictions is a major issue in forecasting HOV use.

Three-person-plus HOV trips were underestimated in OCTD's forecasting approach for 2010 because the base-year 1980 UTPP ratio of one three-person-plus HOV trip to five total HOV trips was used instead of a lower ratio, which would result from restriction of exclusive facilities to three-person-plus HOVs coupled with aggressive destination-end marketing of ridesharing. Certainly, a major increase in three-person-plus HOVs would occur in Orange County, given the significant travel-time savings that eligible users of exclusive facilities would achieve on their commute trips to work. The rate of increase due to travel-time savings will become known to forecasters as more empirical HOV data become available.

The rate of increase in overall carpool formation because of marketing is an unknown that is not receiving adequate attention in forecasting. In Orange County, intensive marketing programs are now under way to promote ridesharing in the major activity centers in the county, with the assistance of employers. The comprehensive ridesharing marketing program, which includes on-site amenities such as preferential parking and other services, should have a strong influence on carpool formation in the future. Although it may be difficult in travel forecasting to account for increases in ridesharing that are due to marketing, these efforts are occurring in Orange County and will influence the use of exclusive facilities. Future HOV travel-forecasting applications must address the influences of aggressive marketing on carpool formation where it exists or suffer the consequences of underestimating HOV use.

Follow-On Activities and Conclusions

The HOV demand estimation approach provided the necessary output for early transitway concept design but is too limited in scope and sophistication for continued use in upcoming OCTD planning activities, especially for a federally sponsored transitway alternatives analysis. Realizing this, OCTD has begun to explore ways to upgrade its current HOV estimation approach and expand its overall in-house travel-forecasting capabilities.

In the fall of 1986, OCTD began a study in an effort to more fully evaluate its future travel-forecasting needs. The major products of this study will include recommended strategic approaches for OCTD to follow in travel forecasting as well as specifications of travel-forecasting hardware and software.

Some of the upcoming travel-forecasting-related projects for which OCTD would need increased demand analysis capabilities are as follows:

- A transitway alternatives analysis will require an areawide travel-forecasting effort. The focus of this project is to estimate the potential bus and HOV use on the proposed transitway segments. Therefore, the objective of the travel-forecasting effort will be to project transit and HOV formation caused by the higher-level transportation service provided and the subsequent travel-time savings to be realized.
- A sensitivity analysis to evaluate how land use and socioeconomic change would affect transportation facility use would also require demand analysis capabilities. OCTD performs sensitivity analyses of travel demand on an as-needed basis in conjunction with other agencies and cities in Orange County.
- A transit route service program would use demand analysis to project how transit service changes would affect the ridership, operating costs, and revenues.
- Corridor and subarea analyses would focus on more detailed evaluations of the traffic movements, transit levels of service, and modal characteristics and compare travel distance with travel time.

REFERENCES

1. *Operations Plan.* Transitway Concept Design Working Paper B-2. Orange County Transit District, Garden Grove, Calif., May 1987.
2. *Selected Characteristics of Travel to Work in 20 Metropolitan Areas: 1977.* Bureau of the Census, U.S. Department of Commerce, Jan. 1981.
3. *Route 55 Commuter Lane Demonstration Project 90 Day Evaluation Report and Six Month Status Report.* California Department of Transportation, Sacramento, Feb. 1986 and June 1986.

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Evaluation of the Cost-Effectiveness of HOV Lanes

CY ULBERG AND KERN JACOBSON

The cost-effectiveness of high-occupancy-vehicle (HOV) lanes was analyzed by comparing the costs and benefits of existing HOV lanes with the hypothetical alternatives of doing nothing or adding a lane for general traffic. Three specific sites in the Seattle area were studied. A life-cycle costing approach was used. The main result of the study was that for the three locations studied, the construction of HOV lanes was the most cost-effective alternative. The marginal net present value of each of the projects was positive (on the order of $50 to $600 per commuter per year, depending on the specific comparison). The marginal benefit/cost ratio was greater than 6 for all cases. Using extreme values for the elements of the model had little impact on the outcome of the study. Using extreme values for any one factor did not come close to reversing any of the findings; it required extreme values for virtually all of the factors for reversal. It is extremely unlikely that all the elements of the model were distorted in a direction to cause this outcome. The methodology developed for this study was incorporated into an easy-to-use personal computer program that assesses the cost-effectiveness of the construction of HOV lanes in other locations. In order to save the costs of extensive data collection, the sensitivity analysis approach developed in this study proved to be a valuable tool in the analysis of sites for HOV lanes.

Congestion is a significant and growing problem in virtually all urban freeway systems in the country. Most of the suggested solutions to the problem entail significant political and financial difficulties. Some say that the only way to solve the problem effectively is to construct additional freeways. However, the construction of new freeways can have severe impacts and in many cases may be ineffective and simply produce more of the same congestion problems. In some cases, light rail systems may preserve adequate mobility in the face of severe congestion. Others argue that the introduction of light rail would have a minimal effect on freeway congestion. In any case, funding for high-capital alternatives such as rail or new freeways is not currently available in most areas.

A less costly alternative is to find ways to make the existing freeways more efficient in handling the demand for movement of people. Several possible ways exist to accomplish this. One of these is the use of high-occupancy-vehicle (HOV) lanes. Adding an HOV lane to a freeway can potentially increase the efficiency of a freeway in at least four ways: (a) by increasing the people-moving capacity of the facility (to provide room for growth in person-trips resulting from future development), (b) by offering high-speed travel to a larger number of people (to decrease the average travel time), (c) by providing an incentive for people to share rides (to increase the number of persons carried per vehicle), and (d) by decreasing vehicle operating costs (by increasing the average speed and reducing the impact of stop-and-go traffic).

PROJECT OBJECTIVES

The objectives of this study were to quantify the financial benefits that result from the introduction of HOV lanes and to compare those benefits with the costs incurred to implement them. Potential benefits of HOV lanes include travel-time savings, reduced vehicle operating costs from smoother operation of the freeways, reduced costs through ridesharing, and the ability to arrive at destinations without having to allow for delays. The primary costs are for the construction and maintenance of the facilities, the enforcement of the use of the lanes, and the subsidy required to provide additional transit and other rideshare services.

APPROACH

In order to compare these costs and benefits, three specific HOV-lane facilities in the Puget Sound area were studied:

1. I-5 from Northgate to the King-Snohomish county line,
2. SR520 east of the Evergreen Point Bridge, and
3. I-405 south of I-90.

On each of these facilities, three alternatives were analyzed:

1. No additional lane construction ("do nothing"),
2. Construction of an additional general-purpose lane ("add a general lane"), and
3. Construction of an additional lane for transit and carpools ("add an HOV lane").

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For all three locations, the third alternative had actually already been implemented.

Many factors were involved in the calculation of the costs and benefits of the alternatives under consideration. To the extent possible, actual data were used in the calculations. However, for many factors, especially in the future, the values were unknown and assumptions were required. In order to test how critical these assumptions were, a sensitivity analysis was employed. A computer program developed specifically for this project was used to explore the impact of extreme assumptions on the final outcomes. Details of the computer program and other technical aspects of the study may be found in a separate report (*1*).

STUDY RESULTS

One of the objectives of this study was to determine the cost-effectiveness of three HOV lanes in this region: I-5 north of Northgate, SR520 east of the Evergreen Point Bridge, and I-405 south of I-90. Those results are summarized here. A second objective of the study was to determine how sensitive the cost-effectiveness results were to the values for the elements of the cost models. The second part of this section deals with this question.

Cost-Effectiveness

Two measures were used to analyze the relative cost-effectiveness of the third alternative compared with either the first or the second one. The first measure was the marginal net present value (NPV), which is the difference between the NPV of the third alternative and those of the other two. The NPV is calculated by subtracting the present value of all the costs of an alternative from the present value of all the benefits. If the NPV of the third alternative were found to be larger than that of either of the other two (in other words, if the marginal NPV were positive), the HOV lanes would be cost-efficient to construct.

The second measure was the marginal benefit/cost ratio. This measure is calculated by dividing the difference in the benefits of two alternatives by the difference in their costs. For instance, if $20 million more in benefits can be realized from the construction of HOV lanes than from doing nothing and the extra costs are only $5 million, the marginal cost/benefit ratio is 4. If this measure is greater than 1, for every dollar spent the return is greater than a dollar.

Table 1 shows the cost-effectiveness indicators for the three locations. Because the marginal NPV was positive for all comparisons, the numbers can be thought of as total savings resulting from implementing HOV lanes rather than from following the other two alternatives. The total savings per commuter in comparison with doing nothing was between $140 and $600 per year. In comparison with adding a lane for general traffic, the savings worked out to between $50 and $80 per year. In all comparisons, the marginal benefit/cost ratio was greater than 6. This means that each extra dollar spent to implement HOV lanes returned at least $6 compared with the other two alternatives.

TABLE 1 COST-EFFECTIVENESS INDICATORS

	Location		
	I-5	SR520	I-405
Marginal Net Present Value (million $'s) – "add an HOV lane" compared with:			
"do nothing"	+146.5	+78.7	+180.1
"add a general lane"	+56.4	+31.0	+14.8
Marginal Benefit/Cost Ratio comparing "add an HOV lane" with:			
"do nothing"	9.08	11.99	15.12
"add a general lane"	7.05	7.83	6.69

Table 2 shows the average overall trip time in the year 2000 for each alternative. HOV-lane speeds are always faster than those in the general traffic lane. In addition, on I-5 and SR520, peak-hour speeds in the general traffic lane were higher for the HOV alternative than for either of the other two alternatives. The cost model showed higher speeds on I-405 in the general traffic lane when the added lane was open to all traffic than when it was used for HOV traffic. The caveat here, however, is that the demand used for the year 2000 was based on a lower-capacity facility. A higher demand probably would not allow the highway to operate as fast as this analysis showed.

Even if general traffic could operate as fast as the analysis showed, there would be little incentive to shift to higher-occupancy vehicles. That result was reflected in the overall net savings shown for the "add an HOV lane" alternative over the "add a general lane" alternative. The personal savings from ridesharing would outweigh the (questionable) advantage that the general traffic lane would have over the HOV lane in travel speeds.

Sensitivity Analysis

A sensitivity analysis was performed on all the factors used in the cost model for the I-5 corridor HOV lane. Using extreme values for any of the factors did not come close

TABLE 2 AVERAGE TRIP TIME FOR ALL MODES IN 2000

Alternative	Location		
	I-5	SR520	I-405
do nothing	27.10	32.84	32.81
add a general lane	23.66	25.25	19.76
add an HOV lane	23.51	23.53	22.42

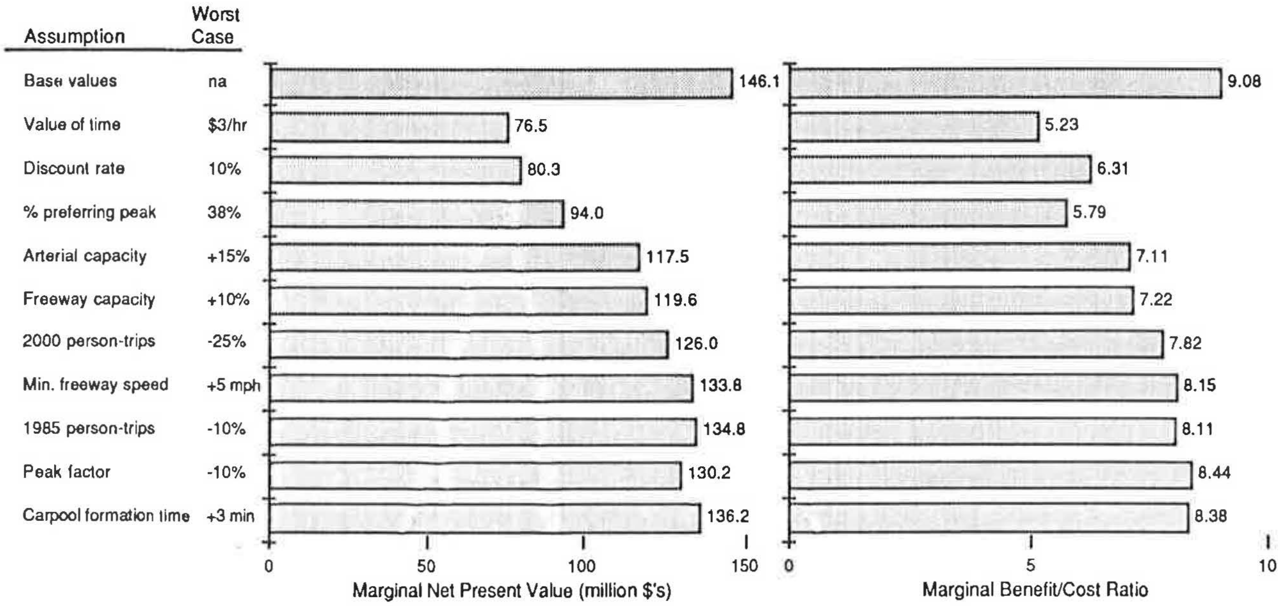

FIGURE 1 **Worst cases compared with "do nothing" alternative.**

to reversing the basic outcome of the study. The 10 most sensitive factors of the model were determined for each of the alternatives and are shown in Figures 1 and 2, in which the resulting cost-effectiveness measures are shown in the worst case for each factor. They are listed in order of sensitivity. One can see that by the tenth most sensitive factor, the worst-case assumption has little impact on the cost-effectiveness outcomes. For three of these factors (percent preferring peak, discount rate, and value of time), rather extreme values were tested. Even with those, the lowest marginal benefit/cost ratio was greater than 5.

All the other factors were related to how congested the corridor is or will become. The less congestion that occurs, the less favorable the HOV lanes are than either of the other alternatives. For instance, if freeway capacity had been underestimated, it would take longer to realize the benefits of the HOV lanes than the analysis showed. If there were more capacity on parallel arterials than had been assumed, it would also take longer before the HOV lanes could help improve the situation. The important point is that, if demand is assumed to increase eventually, errors in these factors only mean that there would be a delay in the time that it would take for the HOV lanes to become as cost-effective as the analysis has shown.

A test was also conducted using combinations of extreme values. Worst-case values for the elements of the model were added consecutively. For the comparison with the "do nothing" alternative, 26 values had to be changed

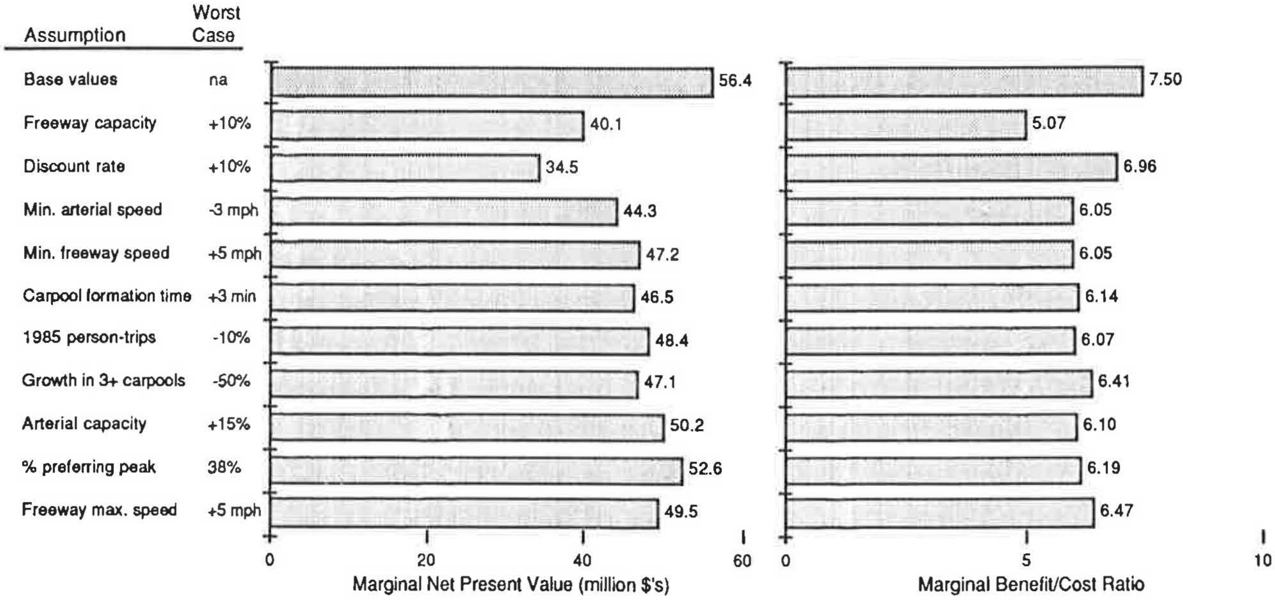

FIGURE 2 **Worst cases compared with "add a general lane" alternative.**

before the HOV-lane alternative was less cost-effective. The comparison with the "add a general lane" alternative required 38 worst-case values to cause a reversal. The likelihood that this many of the base values would be off in the worst-case direction is extremely low.

COST-EFFECTIVENESS EVALUATION METHODOLOGY

In order to evaluate the cost-effectiveness of HOV lanes, the model was designed to address several issues in the measurement of costs and benefits for each alternative:

- How many people would shift from single-occupancy vehicles (SOVs) to carpool, vanpool, or transit if HOV lanes were built?
- To what extent do people depart early in order to arrive on time at their destination?
- Under what conditions do people shift from the freeway to a parallel arterial?
- What is the impact of congestion on speed and total travel time?

In order to accomplish these multiple goals and to test a number of assumptions, some simplification was necessary. Instead of an attempt to analyze the travel patterns between multiple zones of origin and destination, average trip lengths were employed. Distinctions were drawn among the modes under consideration, but the model represented the average person's trip within that mode.

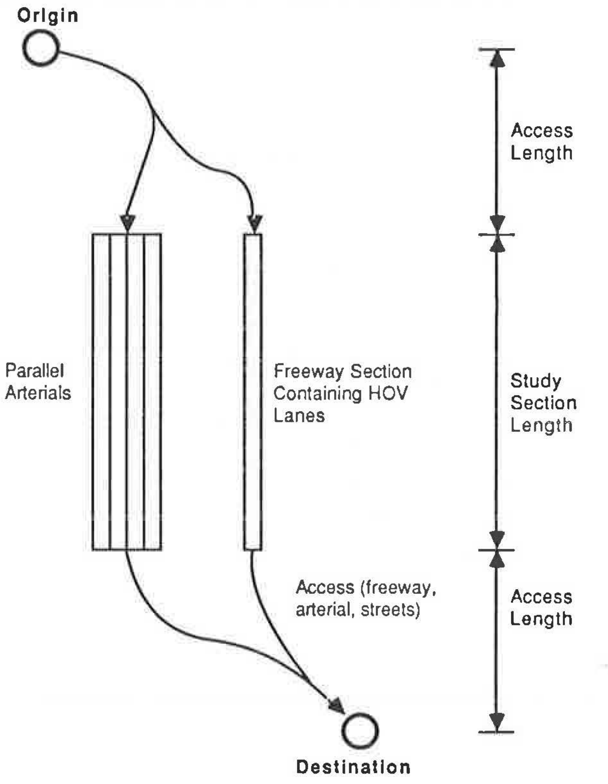

FIGURE 3 Schematic representation of trips using the cost model.

Corridor travel was represented as consisting of only two possible paths, the freeway and parallel arterials. In places such as the I-5 North corridor, multiple arterial paths are available, but in this model they were all represented as one. As shown in Figure 3, trip lengths on the freeway segment and on the parallel arterials were considered equal, as was the access to each of them.

Average trip speeds and times were employed in the analysis. Congestion can vary a great deal from day to day, depending on weather, construction, and accidents. Even though the variability in congestion by itself is an important issue in travel choice, it was beyond the scope of this study to deal with it explicitly.

Overview of the Model

Figure 4 is a flow diagram showing how the cost model works. The model computes all of these factors for six different scenarios. For each of the three alternatives, ("do nothing," "add a general lane," and "add an HOV lane"), costs are computed for 1985 and 2000, resulting in six (3 × 2) scenarios. These years were chosen primarily because person-trip forecasts and other factors for those years were available from the modeling efforts of the Puget Sound Council of Governments (PSCOG). In order to calculate costs for 20 years, a straight line is assumed to pass through these two points.

Modal Assignment

First the peak-period person-trips for each alternative are assigned to different modes. Values for the number of carpools, vanpools, and transit trips are discussed in the next section. The model assigns person-trips to SOVs by subtracting the number of people in the higher-occupancy modes from the total number of person-trips occurring during the peak period.

Path Assignment

Second, a proportion of the trips are asigned to the parallel arterials on the basis of the relative capacity of the arterials. This proportion is adjusted on an iterative basis to minimize the total travel time for all those traveling through the corridor. The optimum total travel time is a legitimate criterion for optimization because it reflects the ability of each traveler to choose on a day-to-day basis between the freeway and the arterial, depending on which one provides faster travel speeds.

The third step is to assign the HOVs to HOV lanes if lanes are part of the alternative. The model assumes that all HOV vehicles travel on the HOV lanes if they are available and if they provide faster travel speeds than the

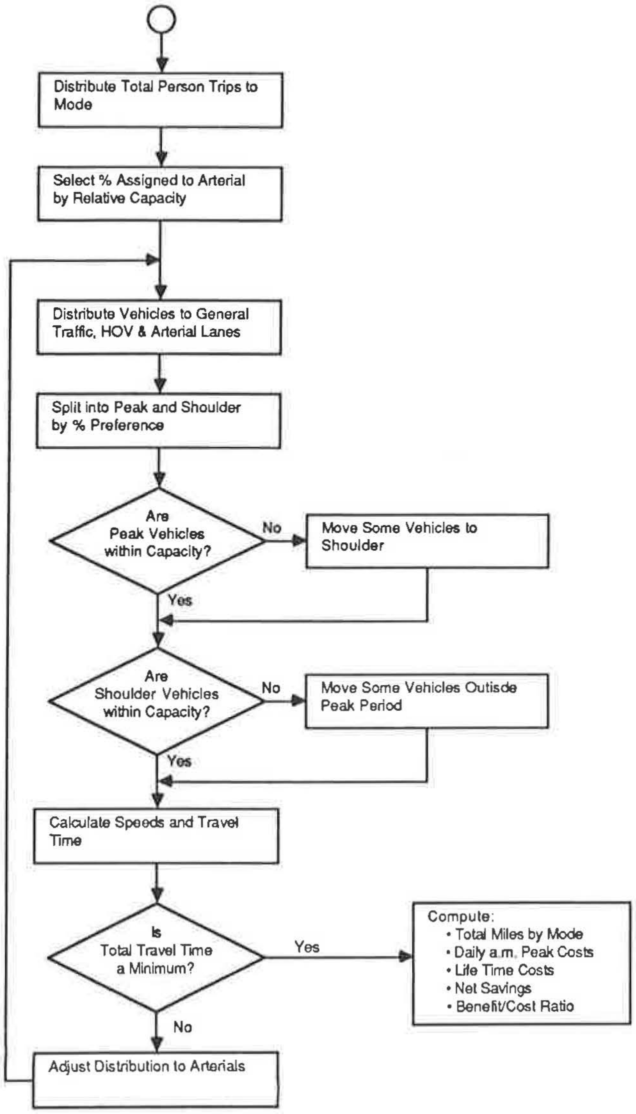

FIGURE 4 Flow diagram for cost model.

other alternatives. If there are no HOV lanes, HOVs are assumed to be distributed in the same manner as all other vehicles.

After the HOVs have been assigned, the model splits the remaining traffic between the freeway and the parallel arterials according to the percentage determined during the iterative optimization process.

Temporal Assignment

The next step is to split the peak-period traffic between the peak hour and the shoulder of the peak. The model assumes that the peak period is 3 hr, with a 2-hr shoulder split on either side of the peak hour. One important element of the model is the percentage of people who prefer to travel in the peak hour. This percentage is influenced by the extent and availability of flexible working hours.

Capacity Checks

The model then checks to determine whether those who prefer to travel during the peak hour can be accommodated by the capacity of the freeway and the arterials during that time. If more people want to travel during the peak than can be accommodated by the free-flow capacity of the highway facilities, the capacity is adjusted downward to reflect the congested conditions. Those who prefer the peak but cannot travel then are assigned to the shoulders, and the model assigns a time penalty to them to reflect the fact that they have to leave earlier than they wish. The length of the time penalty depends on the comparison of demand and capacity in the shoulder. Once the model has assigned the proper number of trips to the peak hour, the process is repeated for the shoulders.

Computation of Speeds and Travel Times

The next steps in the model are relatively straightforward. The model computes speeds for general lanes and HOV lanes on freeways and for the arterials according to speed-flow curves described in the technical report for this project (*1*). From these speeds and the access times used in the model, the total travel times for each mode are calculated.

At this point in the model, total travel times are available and the model uses an algorithm (described in the technical report) to determine whether the traffic has been optimally distributed between the freeway and the arterials. If it has, the model computes total costs. If it has not, all steps are repeated.

Cost Computation

The model computes time costs using the base case for the value of time and adds these to other associated daily costs. Vehicle operating costs are dependent on travel speeds. The model accounts for the extra van and automobile operating costs that are attributable to congestion by adding a percentage (determined by an elasticity) to the costs for each percentage decrease in average travel speed. Transit operating costs take travel speed into account by using a cost model, developed at Seattle Metro, that treats hours, miles, and capital investment costs separately (*2*). The other daily cost included is parking, according to the mode of travel.

For each alternative, daily costs are computed by multiplying the morning peak-period cost by an appropriate factor representing the use of lanes in each direction during each peak period. Annual costs are computed by multiplying daily costs by 250. Using straight-line interpolation, annual costs for each of the years between 1985 and 2005 are computed and discounted at the appropriate discount rate. Total lifetime costs for each alternative include construction costs, annual maintenance costs, and (in the case of the HOV lanes) enforcement costs.

The model treats agency costs, such as construction, maintenance, enforcement, and transit operations, separately from costs borne by the traveler (referred to hereafter as "personal" costs). HOV-lane alternatives generally cost agencies more than the other two alternatives. The agency cost differences are the "cost" part of the marginal benefit/cost ratio. The net savings in personal costs (if any) is the benefit part of the ratio. The marginal NPV simply adds all costs and benefits together, regardless of whether they are agency or personal costs.

DATA REQUIREMENTS AND ASSUMPTIONS

The simplified approach to freeway modeling and benefit-cost analysis employed in this study precluded the necessity of collecting large amounts of data through household or traffic surveys. To the extent possible, existing data were used or assumptions that could be tested were made. Data that were used and the assumptions that were made in order to complete the analysis are described in this section. In addition, the ranges of values that were tested in the sensitivity analysis are outlined.

Person-Trips

One of the main determinants of the degree of congestion in a corridor is the number of people traveling through that corridor. Current estimates of person-trips are probably within 10 percent of the actual person-trips. However, estimates of person-trips 20 years from now are less certain.

In order to start with values that were consistent with each other and with other planning efforts in the region, person-trips in each of the three corridors under consideration were obtained from PSCOG for 1985 and 2000 (*3*). These estimates are currently used for most transportation planning in the region. Table 3 shows the estimated person-trips for the peak 3-hr period for the three corridors under consideration for 1985 and 2000. The 1985 data are probably accurate to within 10 percent. The growth rates to 2000 may vary by 25 percent. For the purposes of this analysis, all three alternatives were assumed to have the same demand.

TABLE 3 THREE-HOUR PEAK-PERIOD PERSON-TRIP DEMAND BY CORRIDOR

Location	Year	
	1985	2000
I-5 (just north of Northgate)	45,100	54,800
SR520 (just east of Evergreen Pt. Brdg.)	17,200	21,300
I-405 (just south of I-90)	13,900	15,900

Number of HOVs

The number of HOVs for the "do nothing" case was assumed to be the same as that for the "add a general lane" case. The number of HOVs in the "add an HOV lane" case was derived from the methodology developed by Charles River Associates [referred to hereafter as the "Parody model" (*4*)]. This method analyzed the impacts of 16 HOV-lane projects and developed a simple methodology to predict shifts to HOVs based on the average of these 16 cases. The method was validated on the I-5 HOV lanes, and the prediction of HOVs was found to be within 5 percent of the actual value observed after 20 months of operation.

The volume of carpools and vanpools was based on current observations on the three facilities being studied. For I-5 and SR520, the current volumes were assumed to be in the "add an HOV lane" alternative. The volumes for the other two alternatives in 1985 were derived by determining the volumes necessary to produce the required volumes in the "add an HOV lane" alternative according to the Parody model. Year 2000 volumes for the first two alternatives were factored from the 1985 volumes proportionally with the increase in total person-trips. Year 2000 volumes for the "add an HOV lane" alternative were computed using the Parody model. On I-405, current carpool and vanpool volumes were used for the "do nothing" and "add a general lane" alternatives, because the HOV lanes had not been in place for long enough to attract much new HOV use. They were also increased for 2000 by using the Parody model.

The number of buses for the three facilities was based on actual counts for 1985 and on figures developed for a long-range planning effort recently completed by Seattle Metro (*5*). Table 4 shows the volumes used for carpools, vanpools, and buses for the three alternatives. In the sensitivity analysis, carpool and vanpool volumes varying 15 percent for the non-HOV-lane alternatives and 30 percent for the HOV-lane alternative were tested.

Percent Preferring Peak

One of the factors that this model takes into account is that when capacity is limited, some people may not be able to travel when they want. For instance, in the morning peak, they may have to leave early in order to guarantee that they get to work on time. However, if they are able, they may shift their working hours so that they do not have to deal with congested traffic conditions. In either case, they may have to travel during times when they would rather not. To account for this, the model computes a time penalty for travelers who are displaced out of the peak hour or out of the shoulder of the peak.

In order to calculate the number of those who are displaced in this way, the model employs an assumption about the percentage who would prefer (all other things being equal) to travel in the peak hour. The model further assumes that all those represented by the person-trips in the

TABLE 4 PEAK-PERIOD HOV VOLUMES

Location	Mode	Alternative					
		Do nothing		Add a general lane		Add an HOV lane	
		Year		Year		Year	
		1985	2000	1985	2000	1985	2000
I-5	2 person carpools	4,713	5,727	4,713	5,727	4,713	5,727
	3+ person carpools	317	385	313	385	458	603
	van pools	24	29	24	29	35	45
	buses	90	104	90	104	103	119
SR520	2 person carpools	900	1,115	900	1,115	900	1,115
	3+ person carpools	293	362	293	362	405	579
	van pools	7	9	7	9	10	14
	buses	87	63	87	63	102	72
I-405	2 person carpools	542	620	542	620	838	1,005
	3+ person carpools	207	237	207	237	320	384
	van pools	11	13	11	13	17	21
	buses	211	25	211	25	21	25

peak period (3 hr long) would prefer to travel during that period. Anyone displaced outside the peak 3 hr also is assigned a time penalty.

The percentage of those who prefer the peak was derived from current actual travel choices. Traffic statistics showed that on I-5 north, about 38 percent of the traffic during the peak 3 hr occurred during the peak hour. Presumably congestion had displaced some people out of the peak hour who would have preferred to be traveling during that time. In addition, vehicle occupancy was greater during the peak hour than in the shoulders of the peak. Because the model deals with person-trips, the relevant data point was the percentage of those who travel in the peak hour. As a base value, the study employed 45 percent as the percentage of those who prefer to travel during the peak hour. A range of 38 to 55 percent was tested in the sensitivity analysis.

Capacity

The capacity of the highway facilities in the three corridors under study had important implications both for the number who could travel when they wanted to and the speeds at which they could travel. Three issues were involved in estimating capacities:

- The capacity of a lane on any facility,
- The number of lanes assumed to represent the corridor's capacity, and
- The relationship between capacity and speed.

The base value for capacity on the freeways was taken from Rutherford and Wellander's study of park-and-ride lots (*6*). The maximum capacity in that study was 1,873 vehicles per hour per lane. For arterials, the estimate varied between 500 and 700 vehicles per hour per lane. Arterial capacities vary widely according to configuration, number of stoplights, and the like. The values used for this study were based on data for urban arterials derived from the most recent version of the Highway Capacity Manual (*7*). The sensitivity analysis tested a range of 10 percent for freeway capacity and 15 percent for arterial capacity.

The second issue was the number of lanes to include in the analysis. For freeways, the number was obvious. However, because this analysis was at the corridor level, some value for the capacity of parallel arterials was required. The I-5 corridor had seven parallel arterials with a total of 17 lanes that were included in the PSCOG estimates of person-trips. Even though no major parallel arterials existed in the SR520 and I-405 corridors, some traveled on side streets to avoid congestion. To account for this, the model used the equivalent of one lane of capacity on parallel arterials for those corridors.

The third factor related to capacity was the speed-flow relationship. Again, this study borrowed from the Rutherford and Wellander study and used the same speed-flow curves (*6*), which were generalized so that assumptions concerning maximum capacity, minimum speed, and maximum speed could be tested to see whether they influenced the outcome of the analysis.

Length

The length of the facilities was fairly precisely known. However, because the parallel arterial capacity was considered in the analysis and the parallel routes were not exactly equivalent to the freeway routes, the model tested the value used for length of the HOV lanes, which was a surrogate for inclusion of the exact paths that arterials took and their influence on the total travel time and lengths experienced by those who traveled in the corridors. The length of each HOV lane was assumed to be within 10 percent of the equivalent length of the facility when the parallel arterials were taken into account.

Access Times

The travel cost model has to account for travel time to the facility that contains the HOV lanes in order to fully analyze the differences among alternatives. Average access times to the freeway corridor were used to compute these costs. A distinction was made among different modes. The model employs a base value for access time for all travelers to the freeway segment that contains the HOV lane and adds some increment to account for the different amounts of time taken by carpools or vanpools to pick up passengers or for passengers to reach a bus stop and wait for the bus. The model also allows a value for access time that is shorter for carpools and vanpools when ramp metering is present to be tested.

The model makes no distinction among the various ways to access a particular mode. For instance, the model does not distinguish between walking to a bus stop or driving to a park-and-ride lot. However, by varying the access time for the bus, different weighting schemes for access could be tested with the model.

Average access times were derived from the PSCOG travel forecasts for the region (*3*):

Mode	*Time (min)*
SOV	11.5
Carpool	12.2
Vanpool	13.5
Bus	21.8

The overall access time was probably within about 15 percent of the actual time. The differential access times for the HOVs were assumed to be accurate within 3 min. All of these extremes were tested in the sensitivity analysis using the cost model.

Total Trip Length

Just as access times differ by mode, the total length of the trip also has an impact on the costs. On average, vanpool trips are longer than all other trips. Carpool trips tend to be somewhat shorter, but not as short as bus trips that use the freeway corridors. Trips in SOVs on the freeway tend to be the shortest.

The model assumes that the average trip length for all trips remains the same. When there is a shift in mode, for example, from SOVs to vanpools, the model keeps the average trip the same by computing a new (shorter) average trip length for SOVs when additional vanpool trips are anticipated. This takes into account the fact that the additional vanpool trips probably take the place of the longest SOV trips.

Base values for trip lengths were derived from PSCOG travel forecasts (*3*):

	Length (mi)	
Mode	*1985*	*2000*
All	10	10
SOV	9.6–10.0	11.7–12.0
Two-person carpool	12	14
Three-person carpool	13	14
Vanpool	20	22
Bus	12	12

The sensitivity analysis tested values 10 percent higher and lower than these.

Minimum and Maximum Speeds

The minimum and maximum speeds allowed by the model affect the way in which the model calculates effective capacities of the facilities and the average speeds under various conditions. The minimum speeds on freeways and arterials determine the point at which travelers shift their time of travel rather than suffer the effects of greater congestion. The base values for the model are 25 mph on freeways and 12 mph on arterials. Raising the minimums would be equivalent to assuming that more people travel at times when they do not want to, but that average speeds are faster. Reducing the minimums would have the opposite effect. In other words, changing the value results in effects that cancel each other out to some extent. For the purposes of this study, the model tested values that were 5 mph higher or lower than the base values for freeway lanes and 3 mph higher or lower for arterial lanes.

Maximum speeds affect the shape of the speed-flow curve. In general, raising the maximum speed raises the average speed under any condition. However, because the model uses the maximum speed as the base upon which to assess the impact of congestion on operating costs (see the next section), raising the maximum speed also results in higher automobile and van operating costs. Changing the value results in effects that tend to cancel each other out, just as with minimum speeds. The base values for this study were 58 mph for freeways and 25 mph for arterials. The sensitivity analysis tested the impact of changing these by 5 mph in either direction for freeway lanes and by 3 mph for arterial lanes.

The model also allows the impact of varying maximum speeds on HOV lanes to be tested. For inside HOV lanes, the base value was the same as that for general traffic lanes. For outside HOV lanes, such as that on SR520, 45 mph was used. Another factor tested was the maximum difference that can exist between the HOV lane and an adjacent general traffic lane. For inside HOV lanes, the base value was a 20-mph maximum differential. For outside HOV lanes, 15 mph was used. The sensitivity analysis explored changing each of these values by 5 mph.

Vehicle Operating Costs

Vehicle operating costs were an important component of the total travel costs used in this evaluation because each alternative had a different mix of vehicles that traveled at different speeds. Three types of vehicle operating costs were included. Automobile operating costs were assumed to be the same, regardless of the number of people in the vehicle. Van and bus operating costs were the other two categories.

The base value for automobile operating costs was taken from research done by the American Automobile Association (AAA) (*8*). The figure for the base year was $0.235 per mile for the entire United States, because AAA does not compute regional costs. This covered all operating costs, including depreciation and insurance. The cost of insurance was used to represent the cost of accidents. The same value was used for 2000, because the model employs current dollar estimates for all costs. The cost of fuel will probably be relatively higher in 2000 than it is now (adjusted for inflation). However, that factor may be offset by the use of more fuel-efficient cars. The sensitivity analysis examined the impact of errors of up to 10 percent in this value.

Van operating costs were obtained from Seattle Metro. The operating cost (exclusive of depreciation) estimated by Metro was $0.304 per mile. Assuming that the vans used for vanpooling had a 5-year life expectancy and that the original cost was $10,000, the depreciation cost worked out to just over $0.11 per mile (132 Metro vans operated for about 2.34 million miles last year). The total van operating cost, therefore, was estimated to be $0.42 per mile. The sensitivity analysis was used to examine the same range of values for van operating costs as that for automobiles.

Operating costs are relatively higher when vehicles are operating in congested conditions. In stop-and-go traffic, fuel efficiency decreases and wear and tear on the brakes, drive train, and engine are more pronounced. To account for this, the model increases operating costs proportionally with decreases in travel speeds resulting from congestion by employing an elasticity for operating costs with respect to speed. The base value used in this study was 0.5 (*6*). In other words, for every 1 percent decrease in the average speed, the average operating cost for automobiles and vans increased by 0.5 percent. In the sensitivity analysis, values varying from 0.25 to 0.75 for this factor were tested.

Bus operating costs were derived from a three-part formula developed at Seattle Metro that uses costs that depend on miles traveled, hours in operation, and number of peak trips. The Rutherford and Wellander study employed the same methodology. The three parts of the formula were updated for 1985. The costs per mile, hour, and peak trip were $1.31, $24.83, and $82.17, respectively. By treating hourly and mileage costs separately, the total operating cost responded to changes in congestion. In the sensitivity analysis, values of up to 10 percent greater or less than these figures were tested.

Bus Fare

Agency costs for operating buses are partly offset by costs borne by the travelers. The base value for bus fare was $0.80, about half of the difference between the current peak-hour fares for one-zone and two-zone trips. Metro has a policy of raising fares only to keep up with inflation. Therefore, the same value was used for 2000 as for 1985. The sensitivity analysis was used to explore the impact of being off by 10 percent in this factor.

Parking Costs

The model uses different costs for carpool, SOV, and vanpool parking. The costs were derived from the PSCOG transportation models and were assumed not to change between 1985 and 2000 (in real terms) (*3*). The average parking cost in the Seattle central business district was $3.71 for SOVs and $3.00 for carpools. Vanpools generally had free parking. Differences as great as 20 percent higher or lower than these figures were explored in the sensitivity analysis.

Construction Cost

The cost of constructing HOV facilities was the major outlay to consider in this analysis of cost-effectiveness. Construction costs for the three HOV-lane facilities were provided by the Washington State Department of Transportation (WSDOT). The costs included both construction and design contracts. Each contract necessary to construct the projects was converted to 1985 dollars using the construction index published in *Engineering News Record* (*9*).

Actual figures were used to represent the cost of construction for the "add an HOV lane" alternative. In order to estimate the costs for construction of the "add a general lane" alternative, assumptions were required. For all three facilities, it was assumed that the cost of constructing an extra lane would be 10 percent less than that of constructing an HOV lane, because signage would not be required and design costs would be less. Note that on SR520 the shoulder would not have been converted to a general traffic lane. The cost of a new lane would have been much higher

TABLE 5 CONSTRUCTION AND DESIGN COSTS

Project	Year							Total (1985 $'s)
	79	80	81	82	83	84	85	
I-5				7316 (7769)	250 (256)		2098 (2098)	10122
I-405						10984 (11074)		11074
SR520	625 (840)			919 (976)	790 (808)			2624
Construction Index	3129.10	3381.62	3725.55	3960.49	4109.53	4171.29	4205.45	
Conversion Factor to 1985 $'s	1.3440	1.2436	1.1288	1.0619	1.0233	1.0082	1.0000	

than the cost of converting the shoulder to an HOV lane. However, this analysis assumed that the shoulder on SR520 could be used as a general traffic lane but that it was equivalent to 30 percent of an additional lane.

Table 5 shows the construction and design costs for the three projects along with totals converted to 1985 dollars (converted costs are given in parentheses). To test the sensitivity of the value for extra costs for HOV lanes, the extra percentage assigned to the HOV lanes was varied between 5 and 20 percent of the total costs in the sensitivity analysis.

Maintenance Costs

Although maintenance is an important consideration in computing the cost for adding a lane to a freeway, additional costs that are incurred because of the lane are difficult to determine. It is impossible to assign maintenance costs to a particular lane on the freeway, and WSDOT does not maintain records by lane. Over a long period, it should be possible to detect the impact of adding a lane. However, not enough historical data existed to detect changes in maintenance costs that occurred when lanes were added to the facilities under study.

Some argue that because of economies of scale, an additional lane does not add proportionally to the cost of maintaining all the lanes on a freeway. Moreover, an additional lane can impose even greater costs than the proportional increase in lanes. One example of this phenomenon is the higher cost of removing snow from a three-lane than from a four-lane freeway. Crews have to move more snow over a greater distance and the effect compounds the costs. HOV lanes that take a shoulder also can increase costs because the shoulder is not available for daytime maintenance crews, which necessitates paying overtime rates for maintenance activities at night.

Because the arguments for and against distributing costs equally over all lanes tend to cancel each other out, the model uses a cost based on the average lane-mile cost of maintenance for all urban freeway lanes and an additional 10 percent cost for the maintenance of HOV lanes compared with an extra general lane.

Maintenance costs vary from place to place depending on the number of bridges and underpasses, the condition of the shoulders, the land use adjacent to the freeway, the type of pavement, and highway geometrics. WSDOT does not keep maintenance records by small enough segments to isolate the total maintenance costs where HOV lanes exist. Therefore, the model used a value of $4,000 per lane-mile per year for all lanes under consideration, which was derived from the Rutherford and Wellander study. Because of the uncertainty involved in using this figure, values as low as $1,000 and as high as $10,000 were tested in the sensitivity analysis.

Enforcement Costs

HOV lanes require extra traffic enforcement to ensure that they continue operating as HOV lanes. The amount of investment determines the extent to which the HOV-lane requirements are observed and therefore how successful such facilities are. The investment in enforcement is a policy issue, and it is difficult to specify exactly how much enforcement should cost.

Currently, HOV enforcement costs fall into two categories: (a) the time and equipment used by the Washington State Patrol (WSP) to monitor the lanes and (b) the HERO program, through which citizens are given a telephone number to call and report violators. Drivers identified in this way receive a series of warnings, although no fine is assessed unless the violation has been witnessed by a WSP officer. The costs for this program are shared between Metro and the WSP.

The WSP recently received a demonstration grant for HOV-lane enforcement. Although the new enforcement operation was not yet in place, an estimate of the extra cost needed to enforce HOV lanes was obtained from this grant, which provided for six extra troopers and one sergeant to supervise them. These officers will be expected to enforce HOV provisions on all HOV lanes in the region. They will, of course, occasionally be called to help with other police work. However, because other officers will also occasionally help with the enforcement of HOV lanes, the funds required to provide these extra officers constitute a good estimate of the investment required to enforce HOV-lane operations.

The cost for each officer and required equipment was about $40,000 a year, for a total of $280,000 a year. These costs were allocated to each HOV lane on the basis of the length of the facility. The resulting costs were $105,000, $115,000, and $60,000 a year for I-5, I-405, and SR520, respectively. The sensitivity analysis included a range of values 25 percent higher and lower than these base values.

Value of Time

The value of time is critical to the outcome of any transportation economics study. A wide range of values has been used. Some studies use one-half the average hourly wage; some use the minimum wage (*10*). Others use alternative bases. Research has shown that using a different value for short and long time differences is appropriate (*11*). Other research has shown that in-vehicle time should be valued differently than out-of-vehicle time (*12*).

The advantage of the approach taken in this study was that the sensitivity of the outcome to the value of time could be tested. In order to simplify the model and to avoid controversy over different approaches that may or may not have made a difference in the outcome of the study, the model employed one value for all types of travel or access time involved in the trips being studied, and a wide range of values was analyzed. The base value was $7.00 an hour, which was approximately two-thirds of the average wage for all workers in this region. It is also consistent with the results of research recently conducted in Texas in which speed choice was used to estimate the value of time (*13*). The range of values tested was from $3.00 to $10.00 an hour.

Discount Rate

The discount rate is used to reflect the difference between the value of money today compared with its value in the future. Economic theory contends that a dollar is more valuable now than the same dollar will be in the future, even when inflation is taken into account. This is because a dollar spent today is no longer available, but a dollar invested today probably will result in the availability of more dollars in the future. The discount rate is used to reflect the potential value of investing a dollar today rather than spending it.

Because most capital decisions involve the question of whether to spend money now or produce later savings, the value of the current investment is discounted by the potential value of the savings in the future. Therefore, the higher the discount rate used, the less cost-effective capital investments appear to be. The Office of Management and Budget (OMB) has specified that a value of 10 percent be used in life-cycle cost analysis of investments. The average difference between inflation and the prime interest rate in the last 40 years has been about 2 percent. These values were used to bracket the base value for the discount rate of 4 percent.

CONCLUSION

HOV lanes may be the most cost-effective approach to moving people on many congested freeways. It is clear that a prerequisite for cost-effectiveness is substantial recurrent congestion. The models developed in this study are easy to use and widely applicable. They are available for use on IBM-compatible personal computers and may be used for estimating cost-effectiveness of HOV lanes and alternatives to them. They are also useful for quick and easy application of the Parody model for estimating use of HOV lanes.

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REFERENCES

1. C.G.Ulberg. *An Evaluation of the Cost-Effectiveness of HOV Lanes: Technical Report.* Research Project Y3399, Task 7. Washington State Transportation Center, Seattle, March 1987.
2. B. Burnett. *Route Cost Model Development and Fare Study Results.* Metro Transit Technical Report. Municipality of Metropolitan Seattle Transit Department, Seattle, April 1983.
3. *Travel Forecasts for 1985 and 2000.* PSCOG Technical Report. Puget Sound Council of Governments, Seattle, 1986.
4. T.E. Parody. *Predicting Travel Volumes for HOV Priority Techniques: Technical Report.* Federal Highway Administration Report FHWA/RD-82/043. FHWA, U.S. Department of Transportation, April 1982.
5. *Multi-Corridor Study.* Municipality of Metropolitan Seattle Transit Department, Seattle, 1986.
6. G.S. Rutherford and C.A. Wellander. *Cost-Effectiveness of Park-and-Ride Lots in the Puget Sound Region.* Research Project Y-2554. Washington State Transportation Center, Seattle, Oct. 1985.
7. *Special Report 209: Highway Capacity Manual.* TRB, National Research Council, Washington, D.C., 1985.
8. *Your Driving Costs.* American Automobile Association, Falls Church, Va., 1982.
9. *Engineering News Record,* 1980–1985.
10. P.R. Stopher. Derivation of Values of Time from Travel Demand Models. In *Transportation Research Record 587,*

TRB, National Research Council, Washington, D.C., 1976, pp. 12–18.
11. T.C. Thomas and G.I. Thompson. Value of Time Saved by Trip Purpose. In *Highway Research Record 369,* HRB, National Research Council, Washington, D.C., 1971, pp. 104–117.
12. F. Southworth and F. Westbrook. *Study of Current and Planned High Occupancy Vehicle Lane Use: Performance and Prospects.* Report ORNL/TM-9847. Oak Ridge National Laboratory, Tenn., Dec. 1985.
13. W.F. McFarland and M.K. Chui. The Value of Travel Time: New Estimates Developed Using a Speed Choice Model. In *Transportation Research Record 1116,* TRB, National Research Council, Washington, D.C., 1987, pp. 15–21.

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High-Occupancy-Vehicle Treatments, Impacts, and Parameters: Procedures and Conclusions

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This paper contains the first part of a report that details the findings of 256 past and present high-occupancy-vehicle (HOV) treatments. The procedures followed and the major conclusions found concerning the 19 specific HOV treatment types studied are presented. Some of these conclusions are that only four treatments (park-and-ride lots, separate roadways, contraflow freeway and arterial lanes, and preferential bypasses at metered ramps) produced the impacts that were expected. Another seven treatments either produced mixed results or had no effect, and for the remaining six treatments either no reportable data had been collected or they had never been implemented. Findings concerning specific HOV treatments were as follows: transit malls and automobile-restricted zones must have an operating transit system in the street and a major pedestrian generator to be effective; reserved-lane operations must not affect reverse-flow traffic and should be physically separated from peak-direction traffic to be effective; contraflow lanes usually have safety problems during off-peak hours or where major turning movements or pedestrian activity exists; concurrent-flow lanes usually need major transit use or a large increase in occupancy to be effective; and finally, a much greater effort must be made by traffic engineers, planners, and researchers to obtain pertinent information about HOV preferential treatments. Volume 2 of this report (available from the New Jersey Department of Transportation) contains a comprehensive bibliography along with a listing of each HOV treatment cited, including the year implemented, size, priority cutoff, hours of operation, current status, and any before-and-after data concerning the impacts that the treatments may have had.

More and more emphasis has been put on the use of mass transit and carpooling in recent years, mainly because of such factors as the trend away from construction of new highways caused by fiscal constraints, limited rights-of-way, and the ever-present, although not always prevalent, energy problems. However, the American love affair with the automobile continues, and the habit of driving alone to work is difficult to change.

One way of enticing people to form a carpool or use mass transit is to give carpools and buses some type of preferential treatment. Preferential treatments for high-occupancy vehicles (HOVs) have therefore become popular transportation system management (TSM) tools for reaching certain objectives such as conserving natural resources or increasing the person-carrying capacity of a roadway at low cost. Examples of such treatments are reserving a lane on a freeway for HOVs, preferential toll charges for HOVs, and special park-and-ride facilities.

In the past, a location was studied for a specific HOV treatment because no systematic approach was available to determine which HOV treatment was best suited for the location. Lack of a systematic approach, in turn, was due partly to the lack of understanding of how well different preferential treatments compared in terms of meeting specific objectives. Therefore, an expensive and detailed feasibility study was necessary to determine whether a specific HOV preferential treatment had the possibility of meeting the proposed objectives for the location.

For example, during the past several years, three different feasibility studies were performed in New Jersey for a preferential HOV lane at three different locations. At one of these locations, Route 444 in Middlesex and Union counties, it was determined that a preferential lane was feasible within 12 mi of the 39-mi study area. After that study, the preferential lane was implemented and subsequently discontinued because it did not meet the objectives. At another location (17 mi of Routes 80 and 95 in Bergen and Passaic counties), it was determined that a preferential HOV lane of 1 mi was feasible for bypassing congestion associated with the George Washington Bridge toll plaza. Steps are currently under way to achieve implementation. However, a preferential lane was not recommended for the remaining 16 mi of the study area. At the third location (6 mi of Route 3 in Passaic, Bergen, and Hudson counties), it was determined that a preferential HOV lane was not feasible.

Because each location was studied independently, large amounts of time and money were expended before it was determined whether the particular preferential treatment should be recommended for implementation. Also, because only one specific preferential HOV treatment was studied at a time, another study was necessary to determine the feasibility of other HOV treatments.

Many preferential HOV treatments have been studied and implemented in other parts of the country. Tremendous amounts of data have been provided by these studies,

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which can be used in identifying the potential of the different treatments in meeting certain objectives. However, no one has compiled these data by each particular parameter associated with the objectives of the HOV treatment.

Therefore, this study had two main objectives: first, to identify the objectives associated with each HOV preferential treatment and from the data of past research, to determine how the parameters associated with these objectives were affected by both successful and unsuccessful HOV treatments; and second, to put this information into an easily accessible manual for project engineers to use in assessing how a specific objective might be affected by implementing a specific preferential treatment.

PROCEDURE

The project was set up in three steps. First an extensive literature review of past work concerning HOV preferential treatments was conducted to compile the material available on the objectives associated with each HOV treatment. Also considered were the parameters used to measure whether the objectives were being reached. Examples of these parameters are travel time, automobile occupancy, transit ridership, and accident rates. These preferential treatments, objectives, and parameters were then grouped in tabular form.

After these groupings had been made, the next step was to determine the opinions of New Jersey's local and state officials on these HOV preferential treatments. In the past, HOV treatments were studied taking only engineering concerns into consideration. Later it was found that the officials were not as enthusiastic as the engineers about the treatment and its attributes. Thus, the main goal during this step of the project was to determine which objectives the respondents thought were the most important for their jurisdiction, whether the respondents thought HOV preferential treatments or more conventional transportation methods best addressed these objectives, and which HOV treatments were supported by the respondents and should be studied for implementation in the future.

Initially, a mailout questionnaire was prepared to obtain these data. However, because most of the local officials were unfamiliar with HOV preferential treatments, it was decided that personal interviews would be more appropriate. HOV treatments, which are relatively new techniques in traffic management, could be better explained and understood in face-to-face meetings. But the list of local officials had grown to over 700, which caused another problem, that is, the large amount of time needed to conduct these interviews. Therefore, plans were again changed and it was decided to interview representatives of the metropolitan planning organizations (MPOs) within the state. In this way, the number of interviews could be greatly reduced and the local point of view could still be obtained because these organizations deal regularly with elected officials. Also, these representatives were more familiar with the use of preferential treatments.

The final step in this study was the preparation of a user's manual detailing experience with HOV preferential treatments. From the earlier literature search, an association was determined among the preferential treatments, the impacts of each treatment, and the parameters used to measure whether the objectives were being met. The information on the effect of HOV preferential treatments on these parameters had not previously been gathered and compiled for easy reference. The resulting manual enables an engineer proposing a preferential treatment to take the parameters associated with the specific location and compare them with both successful and unsuccessful treatments of the past. The comparison will help the engineer in determining the feasibility and possible success of the proposed preferential treatment.

RESULTS

Treatments, Impacts, and Parameters

The first item to be determined was the nature of an HOV preferential treatment. Such treatments were generally considered to be any improvement designed to give those who carpool, vanpool, or use public transportation preference during their trip over those who do not. These treatments are generally installed for use during the peak periods of the day, when congestion exists, and require only minimal cost outlay and a relatively short time to implement. Use of this definition identified 19 preferential treatments, which were then grouped by the four types of preference they provided:

1. Economy: treatments that primarily make a specific trip less expensive for the HOV user,
2. Convenience: treatments that primarily make a specific trip more convenient for the HOV user,
3. Space: treatments that primarily reserve an area for HOV users and require low-occupancy-vehicle users to change their route, and
4. Time: treatments that primarily reduce the travel time for HOV users for a specific trip without requiring non-HOV users to change their route.

The 19 preferential treatments studied, by type, are defined as folows:

1. Economic-preferential treatments
   a. Preferential toll charge: increased toll on a facility for low-occupancy-vehicle users or reduced toll for HOV users;
   b. Preferential freeway congestion price: fee charged to low-occupancy-vehicle users for travel on a congested section of freeway that previously was free (HOV users would continue to travel free);
   c. Preferential parking price: increased fee for low-occupancy-vehicle users to park off the street or reduced parking fee for HOV users;

2. Convenience-preferential treatments
   a. Park-and-ride lot: centralized parking lot for HOV users, accessible by transit;
   b. Preferential parking: reserved parking in the most desirable spaces for HOV users (applicable to large employers, transit station parking areas, and shopping malls);
3. Space-preferential treatments
   a. Exclusive freeway ramp: existing freeway ramp reserved for HOV users;
   b. Transit mall: street reserved for transit and HOV vehicles, principally used within a central business district (CBD) shopping area or a heavy transit transfer area;
   c. Automobile-restricted zone: area of a city in which all automobile traffic is restricted, except sometimes HOV vehicles and public transit (much larger restricted area than a transit mall);
   d. Reduced parking with priority: reduced availability of parking spaces, with priority given to HOV users;
   e. Turning movement restriction: turning movement restricted to HOV users;
4. Time-preferential treatments
   a. Separate roadway: roadway for the exclusive use of HOV users, usually in the median of an existing freeway;
   b. Contraflow freeway preferential lane: freeway traffic lane in the off-peak direction reserved for HOV users;
   c. Contraflow arterial preferential lane: same as the preceding treatment except on an arterial street;
   d. Concurrent-flow freeway preferential lane: freeway traffic lane in the peak direction reserved for HOV users;
   e. Concurrent-flow arterial preferential lane: same as the preceding treatment except on an arterial street;
   f. Exclusive bypass ramp: ramp built exclusively for HOV users to bypass a congested ramp, usually in conjunction with a preferential lane;
   g. Preferential bypass at metered ramp: bypass on the shoulder of a ramp that meters traffic onto a freeway so that HOV users can avoid the queue on the ramp;
   h. Toll-facility preferential lane: reserved toll booth so that HOV users can bypass the queue at the toll plaza;
   i. Signal preemption: traffic signal control, actuated by transmitters located on transit vehicles, that extends the green phase for transit vehicles, thus reducing their delay.

Once the HOV preferential treatments had been determined, the impacts associated with these treatments needed to be determined. In a study (*1*) performed by JHK and Associates and Peat, Marwick, Mitchell and Company for the Federal Highway Administration, a list of goals and impacts was compiled that could be used for all TSM strategies. This list was very helpful in the determination of the final list of objectives, for which 18 positive impacts were chosen.

After the literature review, however, it was found that although some HOV preferential treatments met their stated objectives, they were still determined to be unsuccessful for other reasons. Because of this, a list of 17 negative impacts of these preferential treatments was compiled. These negative impacts are very detrimental to the successful presentation of the treatments to the public.

The next step was the determination of which preferential treatments and which impacts should be grouped, that is, which preferential treatments can be used to meet the positive objectives or to cause the negative impacts to occur. After a review of the literature, a matrix was constructed showing these relationships.

Finally, the parameters that are used to monitor whether the impacts are being affected had to be selected. Thus, Table 1 was compiled, which gives parameters for each of the 35 impacts. The effect that an HOV preferential treatment has on these parameters was used in the third part of this study to determine its success or failure in meeting its objectives.

Questionnaire and Personal Interviews

As detailed in the section headed Procedure, representatives from 12 MPOs were interviewed. Each representative was asked five questions, dealing with (*a*) the objectives associated with the organization itself and with the HOV treatments, (*b*) whether priority should be given and which treatments are applicable in the organization's area, and (*c*) what negative impacts are associated with HOV treatments. Most of the responses to these questions are summarized in Tables 2–4.

From the results of these interviews, the following conclusions can be drawn:

1. Keeping costs down, decreasing congestion, improving the productivity (capacity) of the transportation system, and improving safety are the main objectives and pose the largest problems to the planning organizations.
2. It is generally agreed that HOVs should be given preference, but the specific situation should determine the definition of the HOV.
3. All but one of the 19 HOV preferential treatments were judged to be applicable by at least one planning organization. The two larger metropolitan areas have much more use for these treatments because these are the areas where congestion is greatest.
4. Even though there seems to be support for HOV preferential treatments, very few are being considered for implementation. Preferential treatments are not given top priority in the development of the overall transportation system.
5. The determination of exactly what an HOV treatment is and where and when to implement it is still very abstract. More work needs to be done to determine how to successfully implement an HOV treatment.

TABLE 1 PARAMETERS USED TO MEASURE EFFECTIVENESS OF HOV TREATMENT IMPACTS

Impact	Parameter	Impact	Parameter
Increase person-carrying capacity of roadway	Persons carried, volume-to-capacity comparison	Increase non-HOV operational costs	Parking costs, point-to-point travel costs
Increase bus transit use	Transit passengers, transit passenger-miles of travel	Increase delays for non-HOVs	Person-hours of travel, vehicle-hours of travel, vehicle delay, point-to-point travel time, person delay
Increase bus transit reliability	Schedule adherence, bus breakdowns, travel-time variance	Increase transit operating costs	Operating costs, revenues, deficits
Increase carpooling and vanpooling	Number of carpools and vanpools, automobile occupancy	Increase governmental operating costs	Operating and maintenance cost
Increase safety	Number of accidents, accident rates both per vehicle-miles and per passenger-miles traveled	Increase amount of weaving on roadway	Weaving maneuvers, accidents, accident rates both per vehicle-miles and passenger-miles traveled
Reduce need for future expansion of roadway	Difference between person-moving capability with and without improvement	Increase enforcement costs	Enforcement costs
Reduce congestion on roadway	Total vehicle and person delay	Increase parking needs	Parking reductions, parking needs, parking accumulations
Reduce future capital costs for new construction	Costs saved from sixth objective	Increase energy use initially	Energy consumption
Reduce automobile use on roadway	Number of vehicles, vehicle-miles traveled, automobile occupancy, person-miles of travel	Increase accidents initially	Number of accidents, accident rates both per vehicle-miles and per passenger-miles traveled
Reduce travel time for HOV users and overall	Person-hours of travel, vehicle-hours of travel, point-to-point travel times, vehicle delay	Decrease comfort and convenience for non-HOV users	Perceived comfort and convenience
Reduce travel costs for HOV users	Parking cost, point-to-point travel cost, point-to-point transit fare	Decrease air quality initially	Concentration of pollutants, tons of emissions
Reduce energy use	Energy consumption	Decrease noise quality initially	Noise levels
Improve air quality	Tons of emissions, concentrations of pollutants	Diversion to other routes	Traffic volumes
Improve noise quality	Noise levels	Inconvenience to residents of affected area	Parking needs, walking distance from parking location to destination
Improve comfort and convenience for HOVs	Perceived comfort and convenience, transit load factor, walking distance from parking location to destination	Hamper commercial deliveries	Business owners' complaints
Increase pedestrian and bicycles traffic	Bicycle and pedestrian counts	Negative media coverage	Press articles, editorials
Enhance local commercial access and activity	Dollar sales, employment	Court actions initiated against priority treatment	Court cases
Minimize operating costs for roadway administration	Operating and maintenance costs, operating revenue, operating deficits		

TABLE 2 IMPORTANCE OF EACH IMPACT TO INTERVIEWED PLANNERS

	No. of Responses by Degree of Importance		
Impact	Absolute	Great	Some, Little, or None
Reduced capital costs	9	2	1
Reduced congestion	9	1	2
Increased safety[a]	7	4	1
Increased governmental operational costs	7	2	3
Increased transit use	5	6	1
Increased roadway capacity	6	2	4
Reduced user travel time	3	6	3
Reduced future need to expand roadway	4	3	5
Improved comfort and convenience for HOVs	2	7	3
Increased carpool use	3	4	5
Increased bus reliability	3	3	6
Enhanced local commercial activity	3	3	6
Reduced user travel costs	0	8	4
Reduced automobile use	1	6	5
Improved air quality	1	3	8
Increased pedestrian and bicycle travel	1	2	9
Reduced energy use	0	3	9
Noise impacts	0	0	12

[a] The possibility of increased accidents was mentioned as a negative impact, but the results for 7 of 10 treatments showed no increase in accidents.

TABLE 3 APPLICABILITY OF HOV TREATMENTS IN AREA REPRESENTED BY MPO

Treatment	No. of Positive Responses
Park-and-ride lot	10 (4)
Preferential toll charge	7 (2)
Preferential parking	7 (1)
Toll-facility preferential lane	6 (1)
Automobile-restricted zone	6 (1)
Concurrent-flow arterial preferential lane	6 (3)
Preferential parking price	5
Contraflow arterial preferential lane	5
Transit mall	5
Exclusive bypass ramp	4
Contraflow freeway preferential lane	3
Signal preemption	3
Reduced parking with priority	2
Turning movement restriction	2
Separate roadway	2
Concurrent-flow freeway preferential lane	2 (2)
Preferential freeway congestion price	2
Exclusive freeway ramp	1
Preferential bypass at metered ramp	0

NOTE: Numbers shown in parentheses indicate responses where preferential treatments are now or have been in operation.

This last conclusion leads into the final step of the project, which was to determine whether there is a common link among the successful HOV preferential treatments in the past.

Implemented HOV Treatments and Data

An extensive telephone survey was performed in which state and city transportation agencies across the country were contacted to determine which HOV treatments had been implemented and where, and also to obtain any before-and-after implementation data that might have been collected. Through this survey, 256 specific applications of preferential treatments were pinpointed. Before-and-after data were collected for only about half of these treatments to determine their effectiveness, and only about a fourth had substantial data. All the collected data as well as the entire bibliography are included in Volume 2 (*2*) of this report, which can be obtained by contacting the author.

As shown in Table 5, the format includes the specific locations, year implemented, and other general information for each preferential treatment. Then, as shown in Table 6, for this type of preferential treatment, any before-and-after data for each specific impact are given.

Table 7 presents the impacts that each preferential treatment is expected to have. The amount given in the first column after the name of each treatment is the total number of treatments found in the United States. The shaded blocks represent the expected impact areas. The number

TABLE 4 NEGATIVE IMPACTS THAT MAY CAUSE PROJECT TO BE DROPPED FROM CONSIDERATION

Impact	No. of Responses
Increase accidents initially	6
Inconvenience to residents of affected area	6
Increase governmental operating costs	6
Increase delays for non-HOVs	5
Increase amount of weaving on roadway	4
Increase transit operating costs	4
Diversion to other routes	3
Hamper commercial deliveries	3
Decrease comfort and convenience for non-HOV users	2
Negative media coverage	2
Increase parking needs	1
Decrease air quality initially	1
Court actions initiated against priority treatment	1
Increase non-HOV operational costs	0
Increase enforcement costs	0
Increase energy use initially	0
Decrease noise quality initially	0

TABLE 5 REPORT GIVING GENERAL INFORMATION ON HOV TREATMENTS: TREATMENT L—CONTRAFLOW FREEWAY PREFERENTIAL LANE

	Treatment No.		
Item	L-1	L-2	L-3
Location	Southeast Expressway, Boston, Mass.	I-45N, Houston, Tex.	U.S.-101, San Francisco, Calif.
Year implemented	1971	1979	1972
Length/size	8.5 mi	9.6 mi	4 mi
Number of lanes	1 of 4	1 of 3	1 of 5
Priority cutoff	Bus only	Buses and 8+ vanpools	Buses only
Hours of operation	NB: 7:00–9:30 a.m. SB: 4:00–7:00 p.m.	SB: 6:00–8:30 a.m. NB: 4:00–6:30 p.m.	NB: 4:00–6:00 p.m.
Current status	SB operation suspended in 1971, NB operation suspended in 1976	Operation suspended in 1984	Operational
Violations		10–15 violations per month	No violation problems
Comments	Southbound operation closed after 1971 demonstration because of small benefit; northbound closed in 1976 because operating costs were too high. Lane was only operated during the summer because of safety problems when setting up and removing cones during darkness	Operation was replaced by a separate roadway (K-8)	Connects with concurrent-flow freeway lane (N-2)

in each shaded block indicates the number of treatments that had before-and-after data for that impact. Table 7 shows that the type of data most often collected or calculable deal with congestion reduction, travel-time improvement, increased capacity, capital cost reduction, and safety. Data not usually collected deal with energy, air and noise quality, comfort and convenience, and commercial activity. This closely matches the results of interviews with the state's planning and transit organizations about which impacts are considered important and which are not.

Number and Results of Treatment

In the following paragraphs each preferential treatment will be briefly reviewed, giving the number of treatments, whether the expected impacts occurred, and why they did or did not occur, if possible.

Preferential Toll Charge

Seven cases of preferential toll charges were cited, all of which are still operational. From the data available (seven sites), this preferential treatment really has no effect on increasing the number of carpools and thus improving capacity. However, it does not increase operating costs or cause court actions, either. Therefore, it seems to simply be a way to reward HOV users.

Preferential Freeway Congestion Price

No present or past implementations of this treatment have been found in the United States.

Preferential Parking Price

Two cases of the use of preferential parking prices were cited; one has been suspended because a construction project has removed the parking area. No real data were collected; therefore, no conclusions can be drawn.

Park-and-Ride Lot

In a New Jersey study, the 50 states were surveyed for before-and-after data concerning the use of park-and-ride lots. The results of this study have been published (*3*) and are used as the data base for this treatment. Ten sites were evaluated. Very little in the way of concrete data was available, but a few assumptions can be made. Park-and-ride lots do decrease energy use, vehicle miles traveled, and operating costs, but probably also create additional travel time for the commuter.

Preferential Parking

Five instances of preferential parking treatments were cited; one has been suspended because a construction project has removed the parking area. No data were collected; therefore, no conclusions can be made.

Exclusive Freeway Ramp

Four treatments used exclusive freeway ramps; one has been suspended because of the opening of a separate roadway for buses. From the small amount of data available

TABLE 6 REPORT GIVING BEFORE-AND-AFTER DATA ON HOV TREATMENTS: TREATMENT L—CONTRAFLOW FREEWAY PREFERENTIAL LANE

Treatment No.	Description of Impact
Increase person-carrying capacity of roadway	
L-1	Before implementation there were 5,054 vehicles, including buses, carrying 8,898 people for an average occupancy of 1.76; after implementation there were 5,068 vehicles, including buses, carrying 9,058 people for an average occupancy of 1.79
L-2	During the first week of operation 57 buses carried 804 passengers and 164 vanpools carried 1,539 passengers; after 1 year, 125 buses carried 5,140 passengers and 412 vanpools carried 3,584 passengers, an increase of 6,381 passengers and 316 vehicles
L-3	Very small increase in bus users
Increase bus transit use	
L-1	Before implementation buses carried 2,152 passengers; 3 months after implementation 65 buses carried 2,454 passengers
L-2	During the first week 57 buses carried 804 passengers; 1 year later, 125 buses carried 5,140 passengers
L-3	Currently, 150 buses carry 6,000 passengers, a very small increase in bus patronage.
Reduce need for future expansion of roadway	
L-1	Because approximately 100 vehicle trips were eliminated, it is estimated that it would take an additional year for the roadway to reach capacity
L-2	During both peak periods, 5,000 vehicle trips were eliminated; if one-fourth of these were eliminated during the peak hour, it is estimated that it would take an additional 7 or 8 years for the roadway to reach capacity
L-3	Because of a small increase in occupancy, no reduction is needed

(three sites), this treatment appears to have had no effect on increasing carpools or bus use, but it does afford a travel-time savings to those who use it.

Transit Mall and Automobile-Restricted Zone

Eighteen treatments were found in which transit malls or automobile-restricted zones were used. One has been suspended because it was in a wholesale commercial district and did not attract bus riders and pedestrians. From the small amount of data collected (three sites), it was found that most of the expected impacts did occur. However, some data were contradictory. For example, air and noise quality, pedestrian activity, commercial activity, and transit costs showed a change in the expected direction for one treatment, whereas they stayed the same or changed in the other direction for another. No explanation for this was found. Another facet of this treatment is that it usually reduces the travel time for transit.

Reduced Parking with Priority

One of these treatments was found and is still operational. No data were collected; therefore, no conclusions could be drawn.

Turning Movement Restriction

In five cases, turning movements were restricted, but they were all in conjunction with another preferential treatment, usually a preferential lane. Therefore, the effects of this treatment could not be separated from the effects of the other, more influential treatment.

Separate Roadway

Fifteen instances of the use of separate roadways were found, and all are still operational. From the available data (nine sites), these treatments performed exactly as expected. They increased both bus and carpool use, thereby reducing congestion and the need to expand the roadway. They increased bus reliability by reducing travel time and also reduced emissions and energy use. Media coverage was generally good, and no court challenges were found. This treatment did increase the transit company's operating costs because of the additional service that was usually needed to satisfy demand.

Contraflow Freeway Preferential Lane

Four treatments involving freeway contraflow lanes were found. One was suspended because a separate roadway was opened for HOVs, whereas another was closed in the evening peak because the operating costs outweighed the benefits. From the available data (three sites), these treatments also performed as expected. Bus ridership increased, reducing congestion and the need to expand the roadway. Travel time and cost for HOV users as well as energy use and emissions were reduced. The operating costs for this treatment are high. However, accidents, a major concern with this treatment, showed no signs of increasing during the peak period. During the off peak, accidents increased; it is thought that this occurred because traffic was light and vehicles mistook the priority lane for a general-use lane.

Contraflow Arterial Preferential Lane

In 26 instances, contraflow lanes were used on arterials. Eight have been suspended for the following reasons: high

TABLE 7 HOV PREFERENTIAL TREATMENTS AND IMPACTS: AVAILABLE BEFORE-AND-AFTER DATA

		Incr. Person Carry. Cap. of Rdwy.	Incr. Bus Use	Incr. Bus Reliability	Incr. Car and Vanpools	Incr. Safety	Red. Future Road Needs	Red. Congestion	Red. Capital Costs	Red. Auto Use	Red. Travel Time	Red. Travel Cost	Red. Energy Use	Imp. Air Quality	Imp. Noise Quality	Imp. HOV Comfort and Conv.	Imp. Ped. and Bicycle Traffic	Enh. Comm. Activity	Min. Oper. Costs	Incr. Non-HOV Oper. Costs	Incr. Non-HOV Delays	Incr. Transit Oper. Costs	Incr. Gov. Oper. Costs	Incr. Weaving Movements	Incr. Enforcement Costs	Incr. Parking Needs	Incr. Energy Use Initially	Incr. Acc. Init.	Decr. Non-HOV Comfort and Conv.	Decr. Air Quality Init.	Decr. Noise Quality Init.	Div. to Other Routes	Inconv. Area's Residents	Hamper Comm. Deliveries	Neg. Media Cov.	Court Actions Initiated
Pref. Toll Charges	7	1			1		1		1	1		7											2													3
Pref. Fwy. Cong. Pricing	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0					0	0	0	0		0		0			0	0	0			0	0
Pref. Parking Costs	2				0					0		2								0			0													0
Park-and-Ride Lots	10		0		0						1	9	4	0	0	0						0	1													
Pref. Parking	5				0					0	0					0			0										0							0
Exclusive Fwy. Ramps	4			0	1	0	1		1	0	3	0	0	0	0	0				0	0		0		0		0		0	0	0	0			0	0
Transit Malls Auto Restr. Zones	16		2	0						2			0	2	2	3	2	2	1	1	0	2				3	0		0	1	1	2	0	3	0	0
Red. Parking w/Prior.	1		0		0					0	0					0			0	0	0	0				0	0		0	0	0	0	0			0
Turning Movement Restr.	5			0	0	0					0								0	0	0						0		0	0	0	0	0			0
Separate Roadway	15	7	4	4	1		7	9	7	7	9	0	3	3	0							3	0	0											3	4
Contraflow Fwy. Pref. Lane	4	3	3	0			3	3	3		3	2	1	1	0							0	3	0				3								0
Contraflow Art. Pref. Lane	26	2	3	4			2	9	2		9	2	0	0	0							4	3	0		0		7								2
Concur. Flow Fwy. Pref. Lane	18	8	6	2	9		8	10	8	8	10	2	4	3	0							1	1	1	5		0	9		0	0				5	2
Concur. Flow Art. Pref. Lane	95	19	20	5	7		19	30	19	19	30	2	1	1	0							1	0	0	14	3	0	10		0	0				15	15
Exclusive Bypass Ramp	8			0	0		0		0	0	1	0	0	0	0	0			0						0										0	0
Pref. Bypass at a Metered Ramp	17	7		0	7		7		7	7	8	0	0	0	0	0			0					0	1			1								2
Toll Fac. Pref. Lane	5	4	2	1	1		4		4	4	4	0	0	0	0				0		1	0	3	0	0		0	1		0	0					0
Signal Preemption	16		3	4							7	0								0	3	2	2													

operating costs, low utilization, conversion to a bicycle lane, construction along the roadway, and safety problems. Two others will be suspended in the near future because of safety problems. For the number of treatments, very few data were obtainable. What is available (11 sites) does show an increase in bus use, which reduces congestion and the need to expand the roadway. Travel time and costs are reduced for HOV users. Because of the travel-time reduction, one transit company reported a reduction in operating costs. This treatment has two major drawbacks: government operating costs are high and safety is a major problem.

Concurrent-Flow Freeway Preferential Lane

Eighteen sites of concurrent-flow freeway lanes were found. One has been suspended because of the construction of a light rail system, whereas three others and the operation of another in one direction were suspended because of low utilization of the lane. From the available data (10 sites), most of the expected impacts occurred. Travel time and costs were reduced and bus reliability was improved. However, at a few sites, very little or no increase in carpool use occurred. This was the reason for the closing of two sites where there was also no bus use. Accidents were expected to be a problem for this treatment, but in no case was an extensive increase in accidents reported.

Concurrent-Flow Arterial Preferential Lane

Concurrent-flow lanes on arterials were found in 95 cases, which makes them by far the most popular treatment. However, 22 of these have been suspended for the following reasons: opening of concurrent-flow freeway lane (one case), safety problems (one case), transit strike (one case), high operating costs (one case), opening of light rail system (two cases), enforcement problems (four cases), reconstruction of the roadway (five cases), and low utilization (six cases); one was suspended for an unknown reason. In 11 other cases it has been stated that lack of enforcement or inability to enforce the restrictions may cause the suspension of these lanes. However, for none of the treatments that were suspended for low utilization were there any before-and-after lane use data, and violation rates were reported for almost none of the treatments with enforcement problems. It is therefore impossible to determine how these treatments differ from those that succeeded.

Data were available for 33 sites; the results were somewhat mixed. Most treatments increased carpool and transit use, thus reducing congestion and the need to expand the roadway. Travel time and costs were reduced for HOV users, thus improving bus reliability. The biggest problems with the use of this treatment are enforcement and the possibility of increased accidents, although 7 of 10 treatments showed no increase in accidents. Two aspects that were thought to be problems, negative media coverage and court actions, proved not to be.

Exclusive Bypass Ramp

Eight exclusive bypass ramps were found; one was suspended because of the opening of a light rail line. No real data were collected, so no conclusions could be drawn.

Preferential Bypass at Metered Ramp

Seventeen locations with 294 bypasses were found. Only three bypasses have been suspended, two because of volume problems on the roadway and one because of lack of storage on the ramp. From the available data (for 9 sites and 81 bypasses), most of the expected impacts occurred. Carpool and bus use increased, causing reduced congestion and reduced need to expand the roadway. But at a few sites, the other ramps without bypasses were not studied to determine whether new HOV trips were being generated or whether they were being diverted from the other ramps. Travel times were reduced, and the expected problems, increased accidents and court actions, did not occur. The largest problem that surfaced was that of violation, which was reported as high as 50 percent at some locations. The inability to enforce without being too visible was also stated as a problem.

Toll-Facility Preferential Lane

Preferential lanes on toll facilities were found in five instances, and all are still operational. From the data available (four sites), this treatment does not appear to increase bus ridership, but is merely another way of giving HOV users a time savings, which improves bus reliability without adversely affecting the general traffic. When the lane is operated as a contraflow lane, the operating costs are quite high, but no increase in accidents occurs.

Signal Preemption

In 16 sites signal preemption was the treatment used. At 9 sites these were suspended for the following reasons: new signal system (one case), long delays for buses caused by congestion and an ineffective system (one case), opening of freeway preferential lane (one case), suspension of bus service (one case), high maintenance costs (one case), and long delays for side-street traffic (four cases). Again, for these treatments no before-and-after data were presented to justify the suspensions. From the small amount of available data (nine sites), the treatment appeared to have no effect on ridership but did improve travel time and therefore improved reliability and lowered the transit company's operating costs. It had mixed effects on non-HOV travel times, not affecting them at all at some locations and increasing them, causing delays for both side-street and preemptive-street traffic, at others. Government operating costs appeared to increase.

Summary of Treatment Effects

The number of applications of each treatment and the reasons for suspension of any of them are given in Table 8. In Table 9 the effects of each preferential treatment are summarized. For each type of treatment, the total for each row equals the number of impacts (shaded blocks in Table 7) expected for that treatment.

For six treatments (B, C, E, I, J, P) either no data were available or no applications had been implemented. Therefore, nothing could be said about the 84 possible effects of these treatments. For the remaining 13 treatments, 79 of 210 impacts could not be discussed because no data were available. Data were available for the 131 remaining impacts, 71 of which were affected as expected whereas 24 had a mixture of effects. Finally, for 36 impacts the effects were the exact opposite of what had been expected or they did not occur at all. Most of the latter were negative impacts that did not materialize.

Table 10 is the matrix of preferential treatments and impacts again, this time showing the types of impact for each specific treatment. The results in Tables 8–10 and a review of the data on preferential treatment as a whole may be summarized as follows:

1. A much larger effort must be made to collect the pertinent data when HOV treatments are implemented. It is hard enough to justify reserving a lane or roadway when supporting data are at hand, much less when data are not even available on whether the number of carpools increased. Also, the collection and comparison of more data will help in determining why certain negative impacts occur and how they might be reduced.
2. Nothing can be said about six of the treatments (B, C, E, I, J, P), because no data were available.
3. Four treatments (A, F, R, S) did not appear to increase bus and carpool ridership but were simply a good way of giving HOV users a time or cost reduction. The first two cost the governing agency relatively little, whereas the last two are somewhat expensive. Only Treatment S (signal preemption) could have a negative effect on non-HOV users.
4. Five treatments (D, K, L, M, Q) produced the impacts that were expected of them.
5. Four treatments (G, H, N, O) produced a mixture of impacts.
6. Transit malls and automobile-restricted zones must have an operating transit system in the street and a major

TABLE 8 HOV TREATMENTS: NUMBER IMPLEMENTED AND REASONS FOR SUSPENSION

		Reason for Suspension							
Treatment	No. Implemented	New Construction	Enforcement Problem	Low Utilization	Caused Delay	Other Preferential Treatment Opened or Rail Service Initiated	High Operating Costs	Other	Safety Problem
Preferential toll charge	7								
Preferential freeway congestion price	0								
Preferential parking price	2	1							
Park-and-ride lot	Numerous								
Preferential parking	5	1							
Exclusive freeway ramp	4					1			
Transit mall/ automobile-restricted zone	18			1					
Reduced parking with priority	1								
Turning movement restriction	5								
Separate roadway	15								
Contraflow freeway preferential lane	4					1			
Contraflow arterial preferential lane	26	2		1		1	1		3
Concurrent-flow freeway preferential lane	18			4		1			
Concurrent-flow arterial preferential lane	95	5	4	6		3	1	2	1
Exclusive bypass ramp	8					1			
Preferential bypass at metered ramp	17 (294)								
Toll-facility preferential lane	5								
Signal preemption	16				4	2	1	2	

TABLE 9 SUMMARY OF EFFECTS

Type of Treatment	No Data	Type of Impact Expected	Mixed	Opposite or None
A: Preferential toll charge		1		7
B: Preferential freeway congestion price	25			
C: Preferential parking price	6			
D: Park-and-ride lot	6	3		1
E: Preferential parking	7			
F: Exclusive freeway ramp	19	1		3
G, H: Transit mall/ automobile-restricted zone	8	6	6	3
I: Reduced parking with priority	17			
J: Turning movement restriction	14			
K: Separate roadway	4	12	1	1
L: Contraflow freeway preferential lane	5	10		1
M: Contraflow arterial preferential lane	5	9	1	2
N: Concurrent-flow freeway preferential lane	4	8	8	3
O: Concurrent-flow freeway preferential lane	6	8	8	4
P: Exclusive bypass ramp	15			
Q: Preferential bypass at metered ramp	8	5	1	3
R: Toll-facility preferential lane	12	5		6
S: Signal preemption	2	3	1	2
Total	163	71	24	36

pedestrian generator, such as a commercial business area or a college, for them to be effective.

7. For reserved-lane operations to be effective, the treatment usually should not affect the reverse-flow traffic and at the same time should be physically separated from the peak-direction traffic.

8. Contraflow lanes usually have safety problems during off-peak hours or where major turning movements or pedestrian activity exists.

9. Concurrent-flow lanes must usually have either major transit use or a large increase in general use for them to be successful.

SUMMARY AND CONCLUSIONS

Because of such factors as competing funds for new highway construction, limited right-of-way, and the ever-present energy problems, mass transit and carpool use have received more emphasis in recent years. New ways of enticing commuters out of their cars and into a bus or carpool have been implemented, and this study has reviewed 19 of these HOV preferential treatments. First, the treatments were grouped by the type of preference they produce (economy, convenience, space, and time). Then the anticipated impacts (increased transit use, improved air quality, increased parking needs, etc.) were determined, and finally, the parameters used to measure these impacts (number of transit passengers, tons of emissions, number of parking spaces, etc.) were determined.

Initially, representatives of the MPOs and transit planning agencies in New Jersey were interviewed to determine their interests and views with regard to HOV treatments. From these interviews it was determined that costs, congestion, capacity, and safety are impact areas of major concern. Eighteen of the 19 HOV treatments were judged to be applicable in New Jersey, but very few are being considered. HOV treatments appear to be given low priority in the development of the overall transportation system. Exactly what an HOV treatment is and where and when to implement one are very unclear, and more work needs to be done on what makes a certain implementation a success.

Finally, contact was made with transportation agencies in the United States to determine the number of HOV treatments implemented, to obtain before-and-after data, and to obtain treatment analysis that could help determine why certain treatments are successful. Two hundred and fifty-six applications of the 19 HOV treatments were found,

TABLE 10 HOV PREFERENTIAL TREATMENTS AND IMPACTS: RESULTS

KEY
░ Expected Impact
□ No Data
▒ Mixed Impact
■ Opposite or No Impact

	Incr. Person Carry. Cap. of Rdwy.	Incr. Bus Use	Incr. Bus Reliability	Incr. Car and Vanpools	Incr. Safety	Red. Future Road Needs	Red. Congestion	Red. Capital Costs	Red. Auto Use	Red. Travel Time	Red. Travel Cost	Red. Energy Use	Imp. Air Quality	Imp. Noise Quality	Imp. HOV Comfort and Conv.	Imp. Ped. and Bicycle Traffic	Enh. Comm. Activity	Min. Oper. Costs	Incr. Non-HOV Oper. Costs	Incr. Non-HOV Delays	Incr. Transit Oper. Costs	Incr. Gov. Oper. Costs	Incr. Weaving Movements	Incr. Enforcement Costs	Incr. Parking Needs	Incr. Energy Use Init.	Incr. Acc. Init.	Decr. Non-HOV Comfort and Conv.	Decr. Air Quality Init.	Decr. Noise Quality Init.	Div. to Other Routes	Inconv. Area's Residents	Hamper Comm. Deliveries	Neg. Media Cov.	Court Actions Initiated
Pref. Toll Charges	■			■		■		■	■													■													■
Pref. Fwy. Cong. Pricing																																			
Pref. Parking Costs																																			
Park-and-Ride Lots										■	░	░										░													
Pref. Parking																																			
Exclusive Fwy. Ramps				■		■		■		░																									
Transit Malls		░							░				▒	▒	░	▒	▒	■	▒		▒				░				■	■	░		░		
Auto Restr. Zones																																			
Red. Parking w/Prior.																																			
Turning Movement Restr.																																			
Separate Roadway	░	░	░	░		░	░	░	░	░		░									░													▒	■
Contraflow Fwy. Pref. Lane	░	░				░	░	░		░	░	░										░					■								
Contraflow Art. Pref. Lane	░	░	░			░	░	░		░	░										■	░					▒								■
Concur. Flow Fwy. Pref. Lane	▒	▒	░	▒		▒	░	▒	▒	░	░	░	▒								░	░	░	■			▒							■	■
Concur. Flow Art. Pref. Lane	▒	▒	░	░		▒	░	▒	▒	░	░	■	■								░			░	░		▒							■	■
Exclusive Bypass Ramp																																			
Pref. Bypass at a Metered Ramp	░			▒		░		░	░	░														■			■								■
Toll Fac. Pref. Lane	■	■	░	■		░		░	■	░										■		░					■								
Signal Preemption		■	░							░										▒	■	░													

but only about half of them had any before-and-after data, and only about a fourth had substantial data.

One of the findings from the available data was that the information most often collected was that about which the MPOs were most concerned, namely, costs, congestion, capacity, and safety.

Five treatments (park-and-ride lots, separate roadways, contraflow freeway and arterial lanes, and preferential bypasses at metered ramps) produced the expected impacts, whereas four treatments (preferential toll charges, exclusive freeway ramps, toll-facility preferential lanes, and signal preemptions) did not produce the expected results but were simply a good way of giving HOV users a time or cost reduction. Four treatments (transit malls, automobile-restricted zones, concurrent-flow freeway preferential lanes, and concurrent-flow arterial preferential lanes) produced mixed results on the expected impacts, whereas for the final six treatments (preferential freeway congestion pricing, preferential parking costs, preferential parking with or without priority, turning movement restrictions, and exclusive bypass ramps) no reportable data had been collected or they have never been implemented.

It was generally found that, to be effective, transit malls and automobile-restricted zones must have an operating transit system in the street and a major pedestrian generator. Reserved-lane operations must not affect reverse-flow traffic and should be physically separated from peak-direction traffic to be effective. Contraflow lanes usually have safety problems during off-peak hours or where major turning movements or pedestrian activity exists. Concurrent-flow lanes usually need major transit use or a large increase in general use to be effective.

A much greater effort must be made by traffic engineers, planners, and researchers alike to obtain pertinent information about HOV preferential treatments. These data are needed not only to justify present and future treatments, but also to determine the reason for certain negative impacts. With this knowledge, these negative impacts might even be reduced, making preferential treatments even more attractive to decision makers.

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REFERENCES

1. C. M. Abrams, J.F. diRenzo, S.A. Smith, and R.A. Ferlis. *Measures of Effectiveness for TSM Strategies*. JHK and Associates; Peat, Marwick, Mitchell & Company, Dec. 1981.
2. T. M. Batz. *High Occupancy Vehicle Treatments, Impacts, and Parameters,* Volume 2: *Bibliography and Data.* New Jersey Department of Transportation, Trenton, Aug. 1986.
3. *An Analysis of the Response to New Jersey Department of Transportation's Survey of Statewide Park-and-Ride Development Programs.* New Jersey Department of Transportation, Trenton, 1983.

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Methodology for Estimating Urban Roadway System Congestion

TIMOTHY J. LOMAX

The major urban areas in Texas have experienced a period of unprecedented growth. Along with that growth came significant increases in traffic congestion with corresponding declines in urban mobility. A procedure was developed to estimate the relative traffic congestion levels on urban-area roadway systems. The data elements of the methodology are available from planning agencies and are based on an urban-area designation rather than specific political boundaries. The methodology can be utilized by agencies in urban areas that rely on the freeway and street system to provide person movement. The methodology was illustrated using 1975–1984 data from Austin, Corpus Christi, Dallas, El Paso, Fort Worth, Houston, and San Antonio. An estimate of the number of years before congestion reaches an undesirable level was generated for each major urban area.

Economic growth in major Texas urban areas since the decade of the 1960s has been widely reported, along with the factors that facilitated that growth. Among other factors, the perceived quality of life enjoyed by residents of large Texas cities in the 1960s led to an increase in major business relocation and new business formation in Texas and throughout the Sun Belt. Good transportation and desirable single-family dwellings in suburban areas within relatively short commuting distances to employment centers were important factors, along with the increase in economic activity, in the expansion of major Texas cities. Freeway, expressway, and arterial street systems were expanded or constructed during the initial years of this growth. Inexpensive land and increasing levels of mobility provided by freeways resulted in residential, commercial, and office-space construction at increasing distances from the traditional city centers. Urban Texans have shown that they will locate 20 mi or more from downtown in order to obtain a single-family house on an individual lot.

This choice of residential development has not been without its costs, however, as an analysis of traffic volume demand and roadway capacity indicates. The decade of the 1970s saw a decline in the rate of new freeway and major street construction and a rapid increase in traffic volume due to economic growth. Although lack of funding and concern about available rights-of-way and the environment slowed new freeway construction in many large cities, traffic volume growth rates much greater than those projected produced congested roadways much sooner than had been expected. The promise of near-optimal mobility with the automobile was broken with the rapid rise of congestion.

The mobility decline detailed in the second part of this paper helped to prompt increases in federal, state, and local funding for transportation improvement projects. Expenditures and project justifications are determined on an individual basis, but the condition of the transportation system as a whole is indicative of overall urban mobility. The manner in which projects are chosen, the economic resources expended in their construction, and their impact on reducing commuter travel delay are important factors in determining the amount of support that urban residents will have for new projects.

In the initial section of this paper the development of a procedure used to rank relative mobility in major urban areas is detailed. The data used are generally available from federal, state, and local sources. The general approach is that of a planning-level analysis, which should not require a significant amount of new data collection. No attempt was made in this study to estimate future mobility levels, but rather to illustrate and quantify historical changes in traffic volumes and congestion.

CONGESTION MEASUREMENT METHODOLOGY

Previous research (*1*) into mobility levels in Texas resulted in a methodology to compare urban roadway congestion levels. In this section the purpose, data base, analysis procedure, and major findings of that research effort are summarized.

Purpose

Transportation professionals and the general public are becoming increasingly aware of the traffic congestion levels experienced in major cities. This interest has resulted in research on a procedure that would allow quantitative comparisons of urban areawide traffic volumes and roadway mileage. Obviously, a procedure that could be used by transportation planning agencies with generally available data would be more accessible than one that required new or more extensive data collection.

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Data Base

In the initial relative mobility study, available data proved to be the largest problem. Consistent data that allowed an accurate comparative assessment of urban congestion are not available from any agency or group of agencies. Data collected in several ways by many sources were acquired. In the opinion of the research staff and reviewers of the research report, however, the quantitative measures used in the study did provide a reasonably accurate measure of overall urban mobility. The general nature of the mobility assessment and the variety of data sources as well as the experience of the reviewing agencies combined to provide analysis results consistent with the accuracy level desired. Comparability of the measures was achieved by using several estimates of both travel and area statistics. For example, in defining an urban area, it was not always possible to use jurisdictional limits as the boundaries because of either lack of data on related travel measures or noncomparability of information. County boundaries may appear to provide consistency, but variations in county size as well as percentage of urbanization significantly impaired the utility of county-based data.

Houston's Experience with Declining Mobility

The Houston data detailing the increase in congestion were analyzed to provide a basis for quantitative indicators of mobility decline. The rapid increase in congestion on Houston-area freeways and arterial streets during the 1970s emphasized the need for actions to restore and maintain good mobility.

The disparity between increases in freeway lane miles and in freeway travel during the 1970s in Houston is quantified in Table 1 and Figure 1. The rate of new freeway construction in the 1970s was one-sixth that of the 1960s, whereas daily freeway vehicle miles of travel (VMT) increased at approximately the same rate throughout the 20-year period (*2*). Vehicle registration, population, and traffic volume counts were thoroughly analyzed and also demonstrated the shift from relatively good mobility to relatively poor mobility in only a few years.

Congestion increases were also apparent in the travel delay estimates. Peak-period volume and travel-time information was used to generate the data in Table 2 and Figure 2. Six major radial freeways were evaluated in each of four travel studies conducted by the Houston-Galveston

TABLE 1 GROWTH TRENDS, CITY OF HOUSTON, 1950 TO 1980 (*1*, *3*)

Year	Annual Average Population (1000)	Annual Average Vehicles (1000)	Freeway Travel in VMT Per Day[1] (1000)	Freeway Capacity (Lane-Miles)	Daily VMT Per Freeway Lane-Mile (1000)
1950	596[2]	240	201	24	8.4
1955	692[2]	375	620	100	6.2
1960	938[2]	480	1,044	187	5.6
1965	1,084	625	3,425	456	7.5
1970	1,240	777	7,320	761	9.6
1975	1,440	1,000	11,366	898	12.7
1980	1,604	1,272	16,308	959	17.0
Percent Increase Per Year					
1960-70	2.8	4.9	19.6	15.1	5.5
1970-80	2.6	5.1	8.4	2.4	5.9

[1] VMT--Vehicle-Miles of Travel

[2] As of April 1

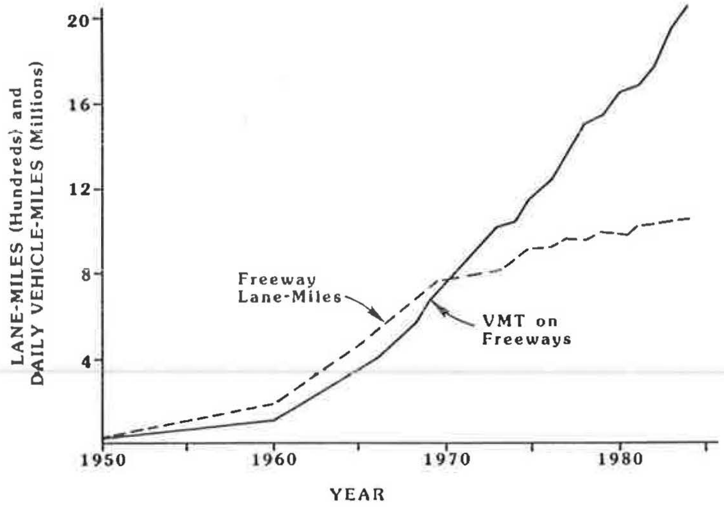
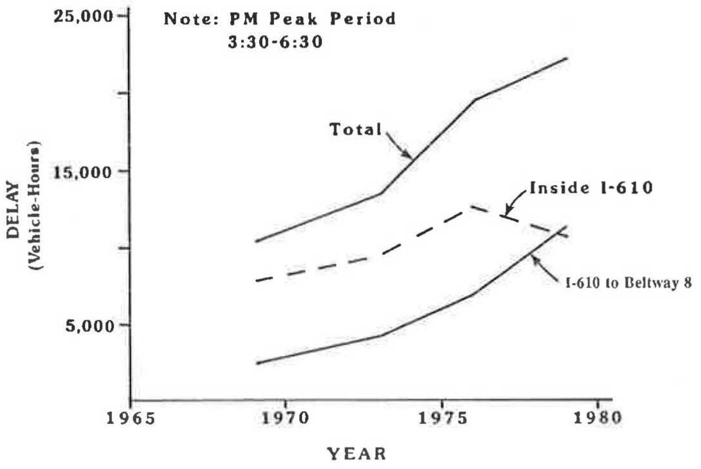


FIGURE 1 Freeway capacity and travel in Houston, 1950 to 1984.

TABLE 2 AVERAGE PEAK-PERIOD DELAY BY FREEWAY SEGMENT FOR SIX MAJOR RADIAL FREEWAYS (*1, 2, 4–6*)

Year	Inside I-610 (Veh-Hours)	I-610 to Beltway 8 (Veh-Hours)	Total (Veh-Hours)
1969	7,880	2,330	10,210
1973	9,370	4,120	13,490
1976	12,650	6,990	19,640
1979	10,970	11,170	22,150



Note: The values presented are total delay for the six freeways studied (I-10W, I-10E, US 59S, US 59N, I-45S, I-45N).

FIGURE 2 Delay by segment for Houston freeways, afternoon peak period (*1, 2, 4–6*).

Regional Transportation Study (HGRTS) (*4*). The dramatic (380 percent) increase in delay in the area from I-610 to Beltway 8 (Figure 2) from 1969 to 1979 indicates the decline in mobility outside the central city area. The decrease in delay inside I-610 (a major circumferential freeway approximately 5 mi from downtown) may be attributable to several factors, including the completion of certain freeway sections and the traffic-metering effect of I-610. On most radial freeways the number of lanes outside Loop 610 is less than that inside the loop. Volumes, however, are not significantly lower, which results in greater congestion outside I-610.

The decline in mobility carries with it a substantial cost. A study performed in Houston (*7*) estimated that in 1981 congestion cost Houstonians $1.9 billion. By most standards, the level of congestion that existed in Houston during the early 1980s would not be acceptable.

The maximum freeway service flow rate for level-of-service C (LOS C) is 1,550 passenger cars per hour per lane (volume/capacity ratio equal to 0.77) for a 70-mph design speed facility (*8*). Using average values for *k*-factor and directional distribution and including some adjustment for trucks and lateral obstructions, these values can be interpreted to indicate that 15,000 vehicles per day (vpd) per lane is an estimate of the beginning of LOS D operation. The development of this value is consistent with the planning-level analysis methodology presented in this paper.

The use of the boundary between LOS C and D as the beginning of congestion is consistent with reports by the U.S. Department of Transportation to Congress on the status of highways in the United States (*9*) (congestion begins at a *v/c* ratio of 0.8) and the AASHTO Policy on Geometric Design of Highways and Streets (*10*) (urban freeways and streets should be designed for LOS C). Although the use of a single number tends to mask the myriad factors used in roadway capacity analyses, the level of accuracy of the data base and the planning nature of the ultimate use of the results of this methodology are compatible with this approach.

Figure 3 quantifies the increase in congested freeway lane miles in Harris County between 1970 and 1985. Although it is not known what percentage of the freeway system exceeding 15,000 vpd per lane (operating at LOS D or worse in the peak hour) is acceptable, it can be assumed that the 10 percent value in 1970 did not suggest countywide deficiencies; however, the 45 percent in 1980 would appear to suggest that such deficiencies did exist.

The data available to the study team did not allow the determination of a specific date at which Houston's traffic problems became critical. For purposes of the overall analysis, however, this was not required. Mobility in Houston could be characterized as "reasonably good" beyond 1970. Peak-period speeds on freeways and major arterials were fairly high, and traffic delay was not a major concern. By the late 1970s, however, peak-period travel delay had doubled from 1970 levels, and volume-per-lane values reflected 2 hr or more of congested operation during both the morning and evening peak periods. Congested freeway lane miles in Harris County (Figure 3) increased from 10 percent in 1970 to 40 percent in 1978. When data for rural areas of Harris County were subtracted from the analysis, the 1978 congested urban freeway mileage approached 50 percent.

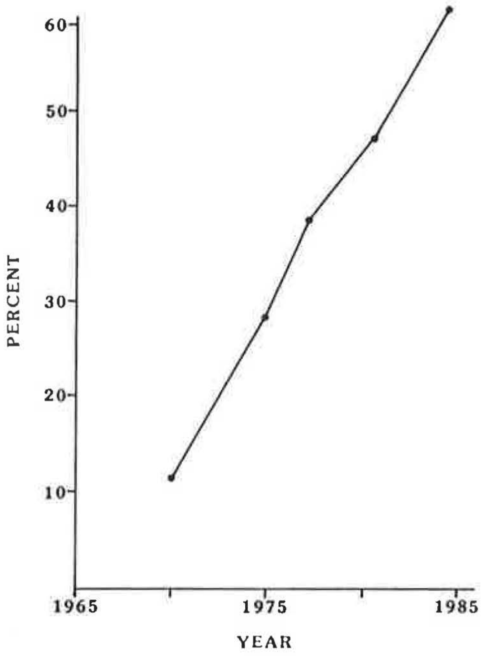


FIGURE 3 Percent of freeway lane miles with more than 15,000 ADT for Harris County (Houston), 1970 to 1985.

Congestion Indicator Determination

The data on mobility decline for Houston indicated that an unacceptable level of transportation service was reached somewhere in the 1975–1976 time frame. That assumption allowed quantitative measures of impending congestion problems to be developed and compared for the major urban areas of Texas. The following measures, listed in apparent order of reliability and usefulness, can be used as guidelines to determine whether congestion in an urban area is becoming critical.

Traffic per Lane

As shown previously, 15,000 vpd per lane for freeways can be interpreted to represent the beginning of LOS D operation. Once traffic has entered that range, congestion is becoming critical. As a measure of approaching congestion, the value of 13,000 vpd per lane used by the Federal Highway Administration in their highway needs estimate (*11*) and by the Texas State Department of Highways and Public Transportation in their project development process (*12*) would appear to represent a more appropriate value.

That standard was also attained on the basis of average urban area in Houston during the period when the degree of mobility was becoming unacceptable (1976–1977).

The corresponding measure for urban arterial streets would appear to be approximately 4,500 vpd per lane. This value occurred in Houston about the mid-1970s and is in general agreement with accepted traffic engineering standards for arterial street operations.

In summary, the following guidelines can be used to mark the point at which urban-area average traffic volumes become critical:

- Freeways: 13,000 vpd per lane,
- Principal arterials: 4,500 vpd per lane.

Percentage of Congested Freeway

The percentage of the freeway system operating under congested conditions (15,000 vpd per lane or more) was determined to be another descriptor of congestion and mobility levels. The relevant data for the Houston area have been presented (Figure 3). From that information, using the 1976–1977 time frame, it appears that once 30 percent of the lane miles is operating at or above 15,000 vpd, mobility has become significantly impaired.

- If the proportion of the county freeway system operating with average daily traffic (ADT) greater than 15,000 vpd per lane is 30 percent, that constitutes congested conditions.

k-*Factor*

As congestion increases, the peak hour begins to spread into a peak period, and congestion exists for longer periods of time. The result is that the percentage of daily traffic that occurs in the peak hour, or the *k*-factor, declines. Decreasing *k*-factor values are thus indicative of the rising off-peak traffic volumes and the lengthening of the peak period. Both of these occurrences are associated with increasing freeway congestion.

Using the *k*-factor as a measure is complicated because of data availability; *k*-factors are readily available only at a limited number of locations, which may or may not be where intense congestion occurs. For example, many sections of roadway in Houston have *k*-factors in the range of 7 percent.

- The systemwide freeway *k*-factor (percentage of ADT in the peak hour) that indicates congested conditions is 9.2 percent.

Summary

These measures are only some of the variables examined during the assessment of possible mobility indicators (*1*). Although all of the measures are limited by the reliability and accuracy of the data base, they are illustrative of urban travel conditions. They are also available without any new data collection requirements, which allows the use of historical traffic data collected during the usual urban planning process. A single variable may not be indicative of the traffic congestion in an urban area, but if all the measures are examined, the relative mobility levels should become apparent.

APPLICATION OF MOBILITY INDICATORS TO TEXAS CITIES, 1975 TO 1984

Urban-Area Definition

Data presented for the various urban areas were derived from several sources, only some of which make a distinction between urban and rural. Many data summaries are for city or county boundaries. This study uses a population density of more than 1,000 persons per square mile as the criterion for urban-area delineation. Data sources with urban and rural classifications for facility mileage and travel volume were used to estimate the quantitative values presented subsequently. It appears that inconsistencies in the data are present to the same degree for all urban areas.

Freeway and Principal Arterial Travel per Lane

Tables 3 and 4 give estimates of lane miles and VMT for freeways and principal arterials in seven urban areas. These were combined into VMT per lane mile of freeway and principal arterials in Table 5 and Figures 4 and 5.

The freeway values in Tables 3 and 5 and Figure 4 are some of the more reliable data used in this study. Figure 4 indicates the critical freeway congestion measure derived from the 1975–1976 Houston value. The volume in the Houston urban area has remained significantly higher than that in other urban areas throughout the study period. Dallas and San Antonio freeway volumes steadily increased during the mid- to late 1970s and increased at a faster rate during the early 1980s. Austin remained at a fairly constant level of freeway traffic volume per lane until about 1981, when freeway congestion began increasing at a rate comparable with that of Dallas and San Antonio. These three urban areas, on the basis of historical growth trends, should hit the critical freeway congestion point well before 1990. Although the Fort Worth freeway travel per lane was not increasing as rapidly as that of Dallas, Austin, or San Antonio, its 1984 value of 10,000 VMT per lane mile has been exceeded by each of those areas since 1980. El Paso and Corpus Christi are characterized by lower, but increasing, values of VMT per lane mile.

The data for VMT per principal arterial lane mile are shown in Tables 4 and 5 and Figure 5. As was the case with the freeway measure, Houston's principal arterials handle more traffic volume per lane than is served in the

TABLE 3 FREEWAY CAPACITY AND TRAVEL IN MAJOR URBAN AREAS (*2, 5, 6, 13–22*)

	Houston		Dallas		El Paso		Ft. Worth		San Antonio		Austin		Corpus Christi	
Year	Lane Miles	Daily VMT (1000)	Lane Miles	Daily VMT (1000)	Lane Miles	Daily VMT (1000)	Lane Miles	Daily VMT (1000)	Lane Miles	Daily VMT (1000)	Lane Miles	Daily VMT (1000)	Lane Miles	Daily VMT (1000)
1984	1,460	23,615	1,620	19,925	345	2,800	965	9,685	785	8,450	290	3,300	165	1,360
1983	1,410	22,555	1,580	18,400	335	2,690	935	9,230	775	7,965	280	2,970	165	1,370
1982	1,375	21,080	1,550	16,870	325	2,560	905	8,625	760	7,600	265	2,530	160	1,300
1981	1,330	19,800	1,515	15,750	310	2,325	880	8,140	760	7,500	250	2,275	160	1,270
1980	1,255	18,405	1,485	15,015	295	2,155	855	7,535	750	7,115	240	2,130	160	1,190
1979	1,265	17,950	1,465	14,620	275	1,975	825	7,145	735	6,680	240	2,100	155	1,235
1978	1,180	16,405	1,450	13,695	275	1,790	795	6,660	685	5,880	240	2,050	155	1,200
1977	1,175	15,650	1,430	12,840	260	1,665	755	6,100	675	5,475	235	2,000	155	1,100
1976	1,210	14,405	1,395	11,555	260	1,545	730	5,670	670	5,080	230	1,900	150	1,070
1975	1,145	13,190	1,350	10,445	260	1,415	720	5,275	660	4,755	215	1,780	150	1,020

TABLE 4 PRINCIPAL ARTERIAL CAPACITY AND TRAVEL IN MAJOR URBAN AREAS (*2, 5, 6, 13–22*)

	Houston		Dallas		El Paso		Ft. Worth		San Antonio		Austin		Corpus Christi	
Year	Lane Miles	Daily VMT (1000)	Lane Miles	Daily VMT (1000)	Lane Miles	Daily VMT (1000)	Lane Miles	Daily VMT (1000)	Lane Miles	Daily VMT (1000)	Lane Miles	Daily VMT (1000)	Lane Miles	Daily VMT (1000)
1984	1,920	10,860	1,650	7,640	800	2,820	825	4,015	980	3,920	380	1,825	320	1,350
1983	1,845	10,350	1,595	7,035	780	2,705	800	3,845	965	3,685	360	1,710	315	1,300
1982	1,785	9,725	1,555	6,440	760	2,600	785	3,660	940	3,525	340	1,595	310	1,250
1981	1,715	9,165	1,510	6,010	740	2,525	760	3,450	890	3,295	325	1,535	305	1,220
1980	1,655	8,565	1,475	5,730	725	2,470	745	3,255	870	3,090	310	1,460	300	1,185
1979	1,585	7,690	1,435	5,400	715	2,410	740	3,150	840	3,000	300	1,410	295	1,150
1978	1,520	7,230	1,395	5,080	710	2,300	725	3,000	805	2,775	280	1,310	295	1,110
1977	1,450	6,925	1,375	4,840	695	2,170	710	2,870	765	2,555	280	1,300	290	1,040
1976	1,380	6,345	1,350	4,490	685	2,070	690	2,725	760	2,470	260	1,210	285	1,000
1975	1,310	5,875	1,320	4,150	675	1,945	665	2,560	740	2,350	245	1,120	285	960

TABLE 5 DAILY VMT PER LANE MILE ON FREEWAYS AND PRINCIPAL ARTERIALS IN MAJOR URBAN AREAS (*2, 5, 6, 13–22*)

	Houston		Dallas		El Paso		Ft. Worth		San Antonio		Austin		Corpus Christi	
Year	Freeway	Prin. Art.	Freeway	Prin. Art.	Freeway	Prin. Art.	Freeway	Prin. Art.	Freeway	Prin. Art.	Freeway	Prin. Art.	Freeway	Prin. Art.
1984	16.175	5.655	12.300	4,630	8,110	3,525	10,035	4,865	10,760	4,000	11,380	4,805	8,240	4,220
1983	15,995	5,610	11,645	4,410	8,030	3,470	9,870	4,805	10,280	3,820	10,605	4,750	8,305	4,125
1982	15,330	5,450	10,885	4,140	7,875	3.420	9.530	4,660	10.000	3,750	9,545	4,690	8,125	4,030
1981	14,885	5,345	10,395	3,980	7,500	3,410	9,250	4,540	9,870	3,700	9,100	4,725	7,940	4,000
1980	14,665	5,175	10,110	3,885	7,305	3,405	8,815	4,370	9,490	3,550	8,875	4,710	7,440	3,950
1979	14,190	4,850	9,980	3,765	7,180	3,370	8,660	4,255	9,090	3,570	8,750	4,700	7,970	3,900
1978	13,905	4,755	9,445	3,640	6,510	3,240	8,375	4,140	8,585	3,450	8,540	4,680	7,740	3,765
1977	13,320	4,775	8,980	3,520	6,405	3,120	8,080	4,040	8,110	3,340	8,510	4,645	7,095	3,585
1976	11,905	4,600	8,285	3,325	5,940	3,020	7,765	3,950	7,580	3,250	8,260	4,655	7,135	3,510
1975	11,520	4,485	7,735	3,145	5,440	2,880	7,325	3,850	7,205	3,175	8,280	4,570	6,800	3,370

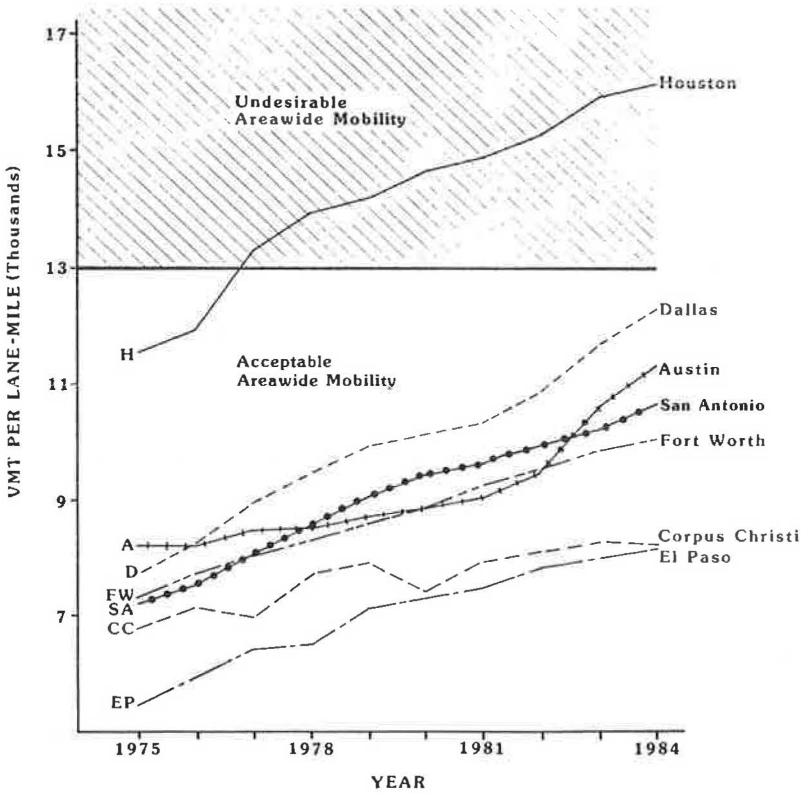


FIGURE 4 Daily travel per freeway lane mile for major Texas urban areas, 1975 to 1984.

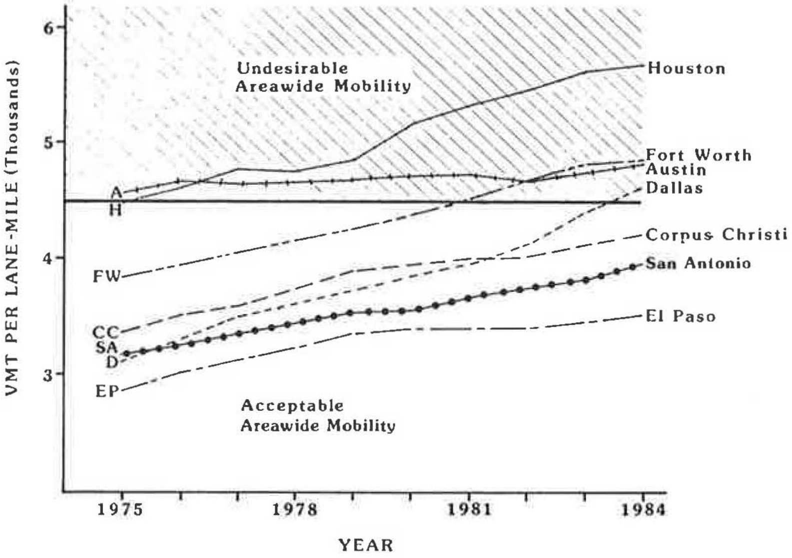


FIGURE 5 Daily travel per principal arterial lane mile for major Texas urban areas, 1975 to 1984.

other areas. The San Antonio, Fort Worth, and Austin arterials, however, are estimated to operate with higher volumes than those in Dallas, which was second to Houston in the freeway rankings. The five highest levels of major urban-area arterial VMT per lane mile exceeded the critical congestion measure in 1984; only Houston exceeded the freeway measure.

The freeway and principal arterial roadway systems were chosen for this analysis because of the availability of data and their importance to areawide mobility. In a subsequent section these two classifications are combined into a single indicator of relative mobility.

Percentage of Congested Freeway

Figure 6 shows the percentage of freeway lane miles in each major urbanized county with ADT volumes in excess of 15,000. Harris County (Houston) reached a congested freeway mileage level more than twice that of the critical measure in 1984. The Dallas freeway system was also beyond the congestion measure in 1984 after a decade of growth that paralleled that of Harris County. Travis (Austin) and Bexar (San Antonio) counties have exceeded 20 percent and have congestion growth trends that nearly parallel those of Dallas and Harris. Based on historic growth trends, Travis, Bexar, and Tarrant (Fort Worth) counties should exceed the 30 percent level before 1990. Although below 15 percent, the El Paso and Nueces County (Corpus Christi) growth rates were fairly high between 1980 and 1984.

The difficulty with urban-area boundary definition and the readily available traffic and roadway link data for counties resulted in the use of county boundaries for this indicator. Some allowance should be made for the differences in county land use patterns and their effect on traffic volumes. Dallas County has a smaller percentage of rural area than the other counties; the percentage of congested freeway lane miles is therefore slightly higher for Dallas County in relation to that for the urban area. Similarly, the percentage of congested miles would be higher for the other six counties if the indicator were calculated for those urban-area (rather than county) boundaries.

k-Factor and ADT per Lane

Automatic traffic recorder (ATR) stations in Texas cities do not provide a statistically accurate sample of urban-area travel. The number of stations is too low, and the locations are not similar in relation to congested freeway segments in every urban area. New ATR stations opened in relatively new and lower-volume freeway sections and older stations taken out of service during freeway reconstruction projects further disrupt the consistency of the data. (These stations were included on the premise that more data were better than consistent data when the latter are not statistically representative of actual conditions.) The percentage of daily traffic that occurs in the peak hour (*k*-factor) and the ADT per lane at these ATR stations are, however, at least somewhat indicative of the growth in freeway congestion.

The peak-hour capacity of a freeway section is relatively constant, and therefore during periods of increasing traffic demand, the traffic volume during the hours adjacent to the peak increases. The trend of increasing freeway volume accompanies a decline in the *k*-factor (Figure 7). Houston, Austin, Dallas, and Fort Worth are at or below the 9.2 percent level determined to indicate impending congestion. San Antonio is somewhat higher than the other areas

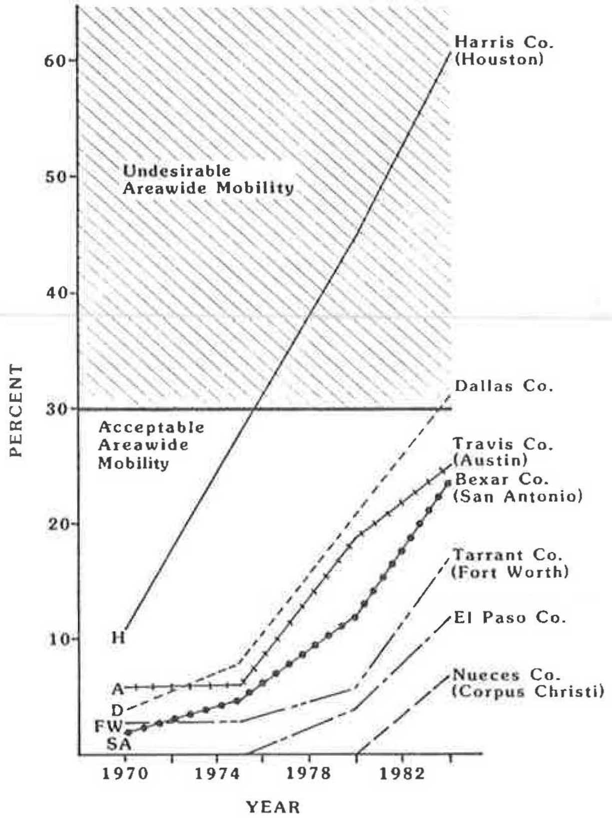


FIGURE 6 Percent of freeway lane miles with more than 15,000 ADT for urbanized Texas counties, 1970 to 1984 (*2, 5, 6, 13, 15, 16, 18, 20*).

because of several new traffic counting stations installed on relatively uncongested roadways in 1976. The El Paso and Corpus Christi data do not currently indicate significant freeway problems.

Daily freeway volume per lane can be calculated from the ATR station data. Figure 8 shows how the cities relate to the 15,000-vpd-per-lane critical value (maximum volume for LOS C) used in Figure 6. Again, the lack of comparability in ATR data reduces the usefulness of this measure, but Figure 8 reveals the same trends noted in other data. Austin, Dallas, Fort Worth, Houston, and San Antonio are above the 15,000-ADT-per-lane level. Austin and Dallas have had significant increases in traffic per lane since 1982.

RELATIVE MOBILITY IN TEXAS CITIES, 1975 TO 1984

The data presented in this paper indicate that varying levels of congestion exist in the large urban areas of Texas. Those areas that do not have severe areawide congestion nevertheless experience traffic problems at specific locations within the urban area.

A 1982 report (*1*) details the analysis technique used in this paper. A relative congestion index was generated by combining freeway and principal arterial VMT per lane (Table 5) for each major urban area. Freeways in most of the large Texas cities carry approximately twice the VMT of the principal arterials (Tables 3 and 4). The value for freeway VMT per lane was doubled to account for this

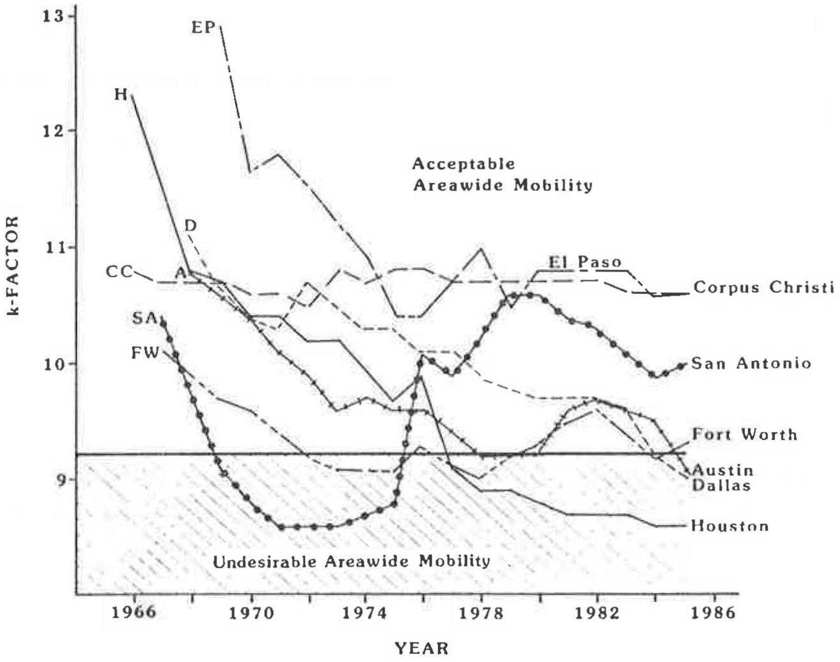


FIGURE 7 Percent of daily traffic volume during peak hour (*k*-factor) at ATR stations in major Texas urban areas, 1966 to 1985 (*5*).

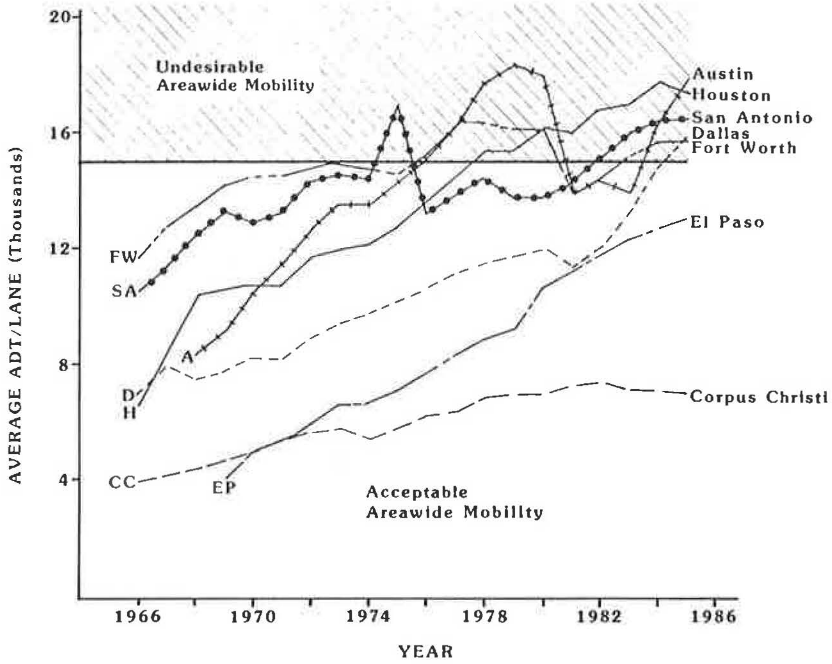


FIGURE 8 Average daily traffic per lane at ATR stations in major Texas urban areas, 1966 to 1985 (*5*).

TABLE 6 AREAWIDE RELATIVE CONGESTION LEVELS

Year	Houston	Dallas	El Paso	Ft. Worth	San Antonio	Austin	Corpus Christi
1984	1.25	0.96	0.65	0.82	0.84	0.90	0.68
1983	1.23	0.91	0.64	0.81	0.80	0.85	0.68
1982	1.18	0.85	0.63	0.78	0.78	0.78	0.66
1981	1.15	0.81	0.60	0.76	0.77	0.75	0.65
1980	1.13	0.79	0.59	0.72	0.74	0.74	0.62
1979	1.09	0.78	0.58	0.71	0.73	0.73	0.65
1978	1.07	0.74	0.53	0.68	0.70	0.71	0.63
1977	1.03	0.70	0.52	0.66	0.66	0.71	0.58
1976	0.93	0.65	0.49	0.64	0.62	0.69	0.58
1975	0.90	0.61	0.45	0.61	0.59	0.69	0.56
Congestion Increase 1975 to 1984	39%	57%	44%	34%	42%	30%	21%

Note: A congestion level higher than 1.00 is considered undesirable.

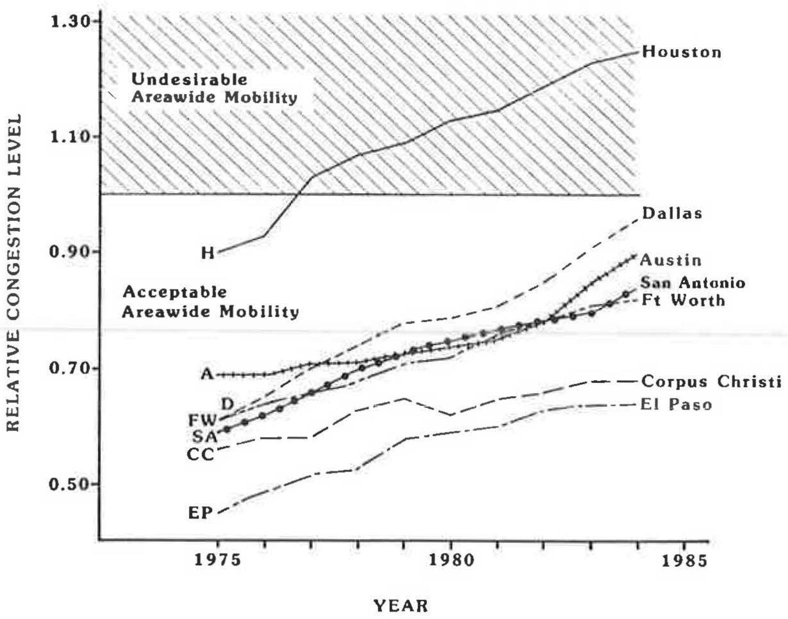


FIGURE 9 Relative congestion levels in major Texas urban areas, 1975 to 1984.

increased importance and added to the arterial VMT per lane. The congestion levels were then normalized, with the critical congestion indicator set equal to 1.0 (*3*):

Congestion index level

$$= \frac{2\text{ (fwy. VMT/lane)} + \text{princ. art. VMT/lane}}{2\text{ (fwy. standard)} + \text{princ. art. standard}} \quad (1)$$

For example,

$$\text{Houston (1984)} = \frac{2(16{,}175) + 5{,}655}{2(13{,}000) + 4{,}500} = 1.25$$

The relative congestion levels in Table 6 are shown along with the urban-area congestion indicator in Figure 9. Houston exceeded the critical level in 1977 and was 25 percent above that level in 1984. Dallas and Austin were within 10 percent of the critical level, and their congestion levels increased at almost twice the rate of Houston between 1980 and 1984. The congestion levels for Fort Worth and San Antonio were approximately equal to those of Houston, Dallas, and Austin in 1980, but have not increased at the same rate as those of Dallas and Austin. The mobility levels for Corpus Christi and El Paso (the inverse of the

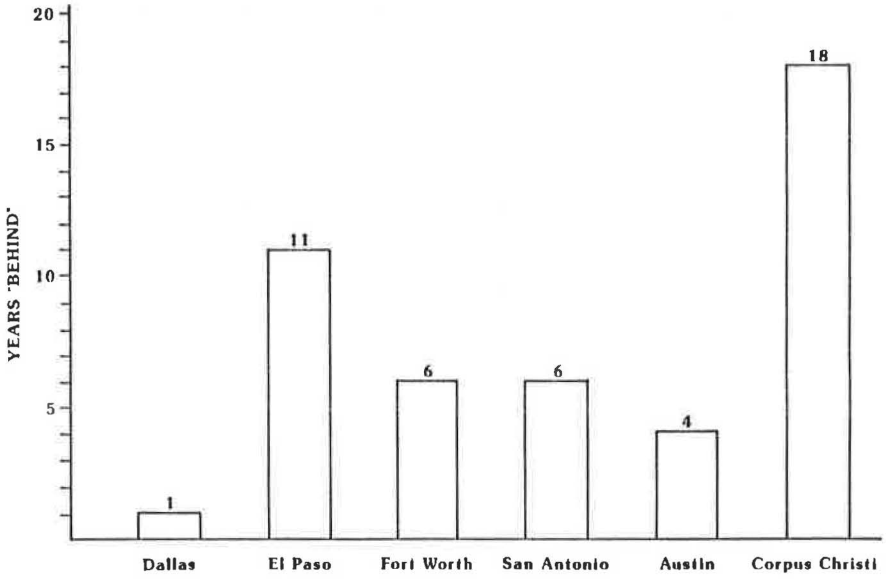


FIGURE 10 Time until attainment of congestion indicator level (extrapolation of 1975 to 1984 data).

congestion levels) have remained generally high, although there has been some decline.

The relationship between freeway and arterial operating conditions should also be examined. The data showed Houston as the only urban area with freeway conditions worse than the congestion indicator, but four areas exceeded the critical arterial value. Greater emphasis is placed on freeway operations, but the important role of principal arterials as alternative routes for freeway trips and as major collection-distribution roadways for freeway access should not be overlooked. A transportation improvement plan that coordinates the use of all roadway resources is more efficient and better able to meet the needs of an automobile-oriented society.

Figure 10 is a summary of the growth trends in the freeway and arterial congestion index between 1975 and 1984. Dallas is estimated to be 1 year from the congestion-indicator level. Austin, San Antonio, and Fort Worth appear to be approximately 5 years away from attainment of the congestion indicator. Austin, however, has had a significantly higher growth rate since 1980, and if that were considered, its estimate of years to attainment would resemble that of Dallas. El Paso is not expected to reach the critical congestion level until the mid-1990s, and Corpus Christi is not expected to have a significant areawide congestion problem before 2000.

It should be noted that the data used in this paper end in 1984. Any assessment of years to attainment of the critical level must be examined with an additional 3 years of mobility decline in mind. Dallas and San Antonio, therefore, may have already exceeded the critical-indicator values, with Austin very near that undesirable congestion level.

REFERENCES

1. *Estimates of Relative Mobility in Major Texas Cities.* Research Report 323-1F. Texas Transportation Institute, Texas A&M University System, College Station, 1982.
2. *Various Houston/Harris County Data.* Houston-Galveston Regional Transportation Study, n.d.
3. *Houston Facts 1981.* Houston Chamber of Commerce, April 1981.
4. *Travel Time and Speed Survey—1969, 1973, 1976 and 1979.* Houston-Galveston Regional Transportation Study, n.d.
5. *Permanent Automatic Traffic Recorder Data—1950–1984.* State Department of Highways and Public Transportation, Austin, Tex., n.d.
6. *Texas Traffic Map—1950–1985.* State Department of Highways and Public Transportation, Austin, Tex., n.d.
7. *Houston Regional Mobility Plan.* Houston Chamber of Commerce, 1982.
8. *Special Report 209: Highway Capacity Manual.* TRB, National Research Council, Washington, D.C., 1985.
9. *The Status of the Nation's Highways: Condition and Performance.* FHWA, U.S. Department of Transportation, June 1985.
10. *A Policy on the Geometric Design of Highways and Streets.* American Association of State Highway and Transportation Officials, Washington, D.C., 1984.
11. *1980—3R Study.* FHWA, U.S. Department of Transportation, 1980.
12. *Ten-Year Project Development Plan Documentation and Support Data.* State Department of Highways and Public Transportation, Austin, Tex., 1986.
13. *Major Thoroughfare Link File—1977, 1979, 1980 and 1983.* North Central Texas Council of Governments, Arlington, n.d.
14. *1984 Vehicle-Miles of Travel Estimates.* North Central Texas Council of Governments, Arlington, Dec. 1985.
15. *Roadway and Population Estimates for the Dallas/Fort Worth Intensive Study Area.* State Department of Highways and Public Transportation, Regional Planning Office, Arlington, Tex., n.d.
16. *Various El Paso County Data.* Planning Office, District 24, State Department of Highways and Public Transportation, Austin, Tex., n.d.
17. *El Paso Urban Transportation Study.* State Department of Highways and Public Transportation, Planning and Research Division, n.d.
18. *Various Bexar County Data.* Planning Office, District 15, State Department of Highways and Public Transportation, Austin, Tex., n.d.
19. *1984 Traffic Volumes.* Austin Transportation Study, 1985.
20. *Roadway Inventory (RI2-TLOG) Tables.* State Department of Highways and Public Transportation, Planning and Research Division, Austin, Tex., n.d.
21. *Form TT Tables.* State Department of Highways and Public Transportation, Planning and Research Division, Austin, Tex., n.d.
22. *Highway Performance Monitoring System.* State Department of Highways and Public Transportation, Planning and Research Division, Austin, Tex., n.d.

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Parking Subsidies and the Drive-Alone Commuter: New Evidence and Implications

RICHARD W. WILLSON

Employers commonly subsidize the parking costs of commuters who drive alone to work. Yet these subsidies lead to inefficient commuter mode choice. Two 1986 surveys of downtown Los Angeles commuters are described that add to what is known about parking subsidies. The surveys reveal that most downtown Los Angeles employers subsidize parking to a substantial degree. Many drive-alone commuters pay nothing for parking. These subsidies (and employer decisions regarding them) influence the decision-making process of commuters and distort the market for commuter parking spaces. The author discusses how knowledge about subsidies can clarify current issues in transportation and argues that subsidies must be considered in the development of transportation policies and programs. Finally, consideration is given to how research efforts should address the parking subsidy issue. For example, the degree and nature of the relation between parking subsidies and mode choice require further investigation. How sensitive are commuters to parking prices when the subsidized price is so low compared with other out-of-pocket and time costs? And how do employers make decisions about the parking and other transportation benefits they offer? In conclusion, a number of research areas are suggested for further investigation.

Traffic congestion continues to dominate the planning agenda in central city and suburban areas. Many point to the drive-alone commuter as a major contributor to peak-hour congestion. In response, transportation demand management (TDM) strategies focus on inducing drive-alone commuters to shift to carpool, vanpool, and transit.

An array of public and private incentives is used to achieve this objective. Transit improvements, ride-matching services, employer incentive programs, and transportation management organizations are just a few examples. However, it is now well established that these incentives compete against a powerful incentive for driving alone—free or subsidized employee parking.

In this paper, results of surveys of commuters and employers in downtown Los Angeles are added to the existing evidence on the extent of employer subsidies for parking. Characteristics of the subsidies, their impacts on commuter mode choice, and the implications of these findings for transportation and parking policy are discussed. Finally, a series of research questions is posed for subsequent investigations.

Some background on downtown Los Angeles is needed to understand the context for the findings. Office space in the downtown area has grown rapidly in the last two decades, primarily in the financial sector. The downtown area has the largest office concentration in the region and is the hub for the regional freeway and bus systems. Both light and heavy rail transit systems are being built to serve downtown. Finally, transportation demand programs are being implemented by the developers of new projects.

Traffic congestion on local streets and the freeway systems is worsening, and local politicians and civic leaders are calling for further action. The density of downtown development projects is being scrutinized more closely than had been done previously. Moreover, development control ordinances and ballot initiatives have been proposed and adopted in other parts of the city and may soon apply to the downtown area.

Local government agencies are working on transportation problems. However, not all agree on solutions, especially those relating to parking policy, which is perhaps the most acrimonious issue of all. The private sector is beginning to come to grips with the issue of parking subsidies but so far is not committed to any change.

PARKING SUBSIDIES AND MODE CHOICE

Shoup has argued that free or subsidized parking has a major impact on mode choice (*1*). He uses census data, predictive models, and case studies to show the effect of subsidized parking on drive-alone commuting patterns, and reveals that according to national census data, 93 percent of all commuters park free at work (*1*).

Shoup shows that for most commuters, free parking is a larger financial incentive than free gasoline. In addition, parking subsidies are not taxed as income and are therefore of even greater benefit to employees. Overall, he concludes that at least 20 percent of all those who park free and who drive alone would switch to a rideshare mode if they had to pay for parking (*1*).

This is not to argue that other factors are not significant in determining mode choice. Commuters base their mode selections on a complex set of criteria including cost, convenience, safety, travel time, and social reasons. However, parking subsidies are a powerful influence—one that policy makers can change through public- and private-sector actions.

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Some of the difficulties with parking subsidies are evident in downtown Los Angeles. For example, Metro Rail (a proposed $4.4-billion, 18-mi subway) will increase mobility in a major travel corridor leading to the downtown area. Sizable ridership is needed to justify the capital costs of the system. However, many downtown commuters do not pay for parking. Employers provide this free parking in an area with some of the highest land costs in the western United States. The result is competing incentives—extensive public subsidy for transit and low automobile commute costs resulting from private parking subsidies.

CHANGING PARKING SUBSIDIES

A number of solutions to the parking subsidy problem exist. For example, "cashing out" parking subsidies gives employees more choice about how to spend that money. Currently, most employees cannot trade a parking benefit for other benefits or income. Parking taxes and other pricing strategies can also be used. In a study of parking management strategies, DiRenzo et al. organize pricing tactics into three categories (*2*):

- Parking rate increases achieved through general rate increases, revisions to rate structure, parking taxes, and parking surcharges;
- Differential pricing programs for short-term versus long-term parking, carpools and vanpools, and other programs; and
- Changes in employer parking subsidy programs, including reduction in subsidies and transit-HOV subsidy programs.

Employer parking subsidies can be removed or reduced by (a) increasing rates in employer lots, (b) dropping subsidies for commercial lots, or (c) cashing out parking benefits with a monthly transportation subsidy (*2*).

The evidence of the effectiveness of these alternatives is limited, especially for individual employer programs. The strongest case is in Ottawa, Canada, where the federal government increased parking rates for their employees from no charge to 70 percent of the commercial rates. There was a 23 percent reduction in the number of employees driving to work, an increase in automobile occupancy from 1.33 to 1.41, and a bus ridership increase of 16 percent (*2*).

Despite this background, parking subsidies are often not directly addressed in transportation traffic mitigation programs. The issue of parking subsidies is perceived as being too intrusive to the business operation of developers and other employers. Critics also question the ability of the private sector to regulate parking prices and to enforce those regulations.

Examples of two traffic mitigation programs illustrate this point. One approach is to require rideshare incentives but not to directly address parking subsidies or pricing. The Coastal Corridor Transportation Specific Plan in Los Angeles is an example of this approach. This plan gives developers credit on a traffic impact fee if they provide rideshare incentives such as transit passes or carpool and vanpool incentives (*3*).

A step closer to effecting changes in parking subsidies is the requirement included in new developments by the Los Angeles Community Redevelopment Agency (CRA). Developers must meet a performance target for rideshare participation in their project or face penalties (*4*). The agreement does not specify the programs and incentives for meeting the targets. However, developers and employers are likely to find adjustments to parking prices and subsidies a cost-effective way of achieving the performance target.

NEW EVIDENCE ON EMPLOYER PARKING SUBSIDIES

The data presented in this section draw from two recent surveys of commuters and employers in downtown Los Angeles. The first is an extensive baseline survey of more than 5,000 employees in 118 companies (*5*). It was conducted in June 1986 and included both employee and employer surveys. CRA commissioned the survey; Barton-Aschman Associates, Inc. and Recht Hausrath & Associates completed it.

The survey objectives were to provide information on the travel conditions, travel characteristics, and the mode split of downtown office commuters. It also determined mode-split characteristics by subgeographic area and by socioeconomic and employer attributes. CRA is using the survey to establish rideshare participation targets for rideshare program agreements. Survey findings will also help define transportation management programs for the downtown area.

As mentioned, the baseline survey included both employers and employees. CRA required statistical confidence for the ridesharing percentages from the employee survey. However, the employer survey did not achieve the same level of statistical confidence, because the sample was smaller and the population was not representative of all employers in the study area. The employer survey did provide a reasonable cross section of office employers and provided new information about their parking policies. With this caveat, the results of the employer surveys are used in some of the analyses that follow.

The second survey consisted of telephone interviews with 226 downtown workers, probing their attitudes regarding parking. The survey was completed in August 1986 to be used in the design of a peripheral parking program (*6*). CRA commissioned this survey also; Kotin, Regan Mouchly, Inc. was the consultant.

Information relating to parking subsidies by employers is derived from these surveys and presented in key categories of interest. Overall, the data show extensive employer involvement and subsidization of parking for commuters.

Characteristics of Employer Subsidies

Employer subsidy of parking is widespread—only 14 percent of the employers who responded to the baseline survey do not provide such subsidies. Twenty-nine percent of employers offer free parking to all employees. Apart from a 19 percent nonresponse, the remainder of the responses fell somewhere in the middle—free parking for some employees or subsidy for some or all employees. Figure 1 details the responses to this question.

The finding of the baseline survey on parking subsidy is comparable with that of a previous survey conducted in 1974, which indicated that more than 25 percent of the daily downtown automobile commuters parked free (*7*). Therefore, free parking is just as prevalent now as it was in the 1970s. This has occurred despite the fact that employer cost for the subsidies has increased substantially, because parking price increases have far outpaced inflation.

These data confirm that employers are the ones who make critical decisions that influence employee mode choice. Public policy approaches that appeal to commuters to change modes must address free or subsidized parking and the decision-making processes of employers. In addition, efforts to model commuter mode choice must use the "after subsidy" price to commuters as an independent variable, not the quoted parking costs.

Employer response to questions about the amount of parking subsidy indicate a broad range of subsidies. The median daily parking cost is approximately $5 (*6*). One-fourth of the employers surveyed provide a $5 subsidy or more, generally indicating that they pay the full cost of parking (*5*). Other subsidies were fairly evenly distributed among lower ranges, representing a variety of parking prices and subsidy levels. From the aggregate reported average parking subsidy, the median subsidy is $3.71 per day (*5*). Figure 2 provides more details.

These subsidy levels represent a substantial transportation investment by employers. The annual cost to an employer with 500 employees (70 percent of whom drive) to provide a parking subsidy of $3.71 per driver is $339,000. Taking this a step further, the estimated annual private-sector expenditure on parking subsidies in downtown Los Angeles is $118 million (median subsidy of $3.71 per day per driving employee, or $968 per year times 175,000 employees times 70 percent of employees who drive). This amount is almost equivalent to the entire private-sector contribution to the Metro Rail project through benefit assessment.

FIGURE 1 Los Angeles CBD employee travel survey: Question 36—employee parking subsidies (*5*).

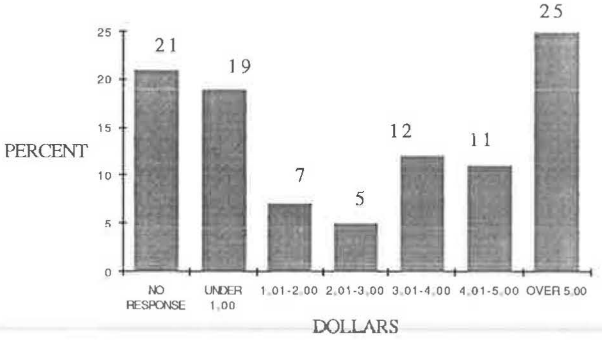

FIGURE 2 Los Angeles CBD employee travel survey: Question 15D—average parking subsidy (*5*).

Parking subsidy costs are much greater than the cost of employer-provided rideshare programs, as was indicated in a national survey examining employer involvement in employee transportation. Sixty-five percent of employers spend less than $5 per employee per year on rideshare programs. The category with the highest response, 7 percent, consisted of employers who spend over $50 per employee per year in rideshare costs (*8*). Clearly, the employer cost is far lower for rideshare programs than for parking subsidies.

The opportunity cost of parking subsidy expenditures is significant. Not only does the money represent lost income for either the firm or the employee, but it encourages commuting patterns that increase congestion. Much of the cost of solving the resulting congestion problems then falls on the public sector. Road widenings, environmental mitigation, and other programs are required, at considerable expense.

An additional area of interest is the basis on which employers provide subsidized parking. There was significant nonresponse to this question (66 percent), so the response must be interpreted with caution. Most responses fell into two categories—seniority (16 percent) and job classification (13 percent). Because employers rely on these factors, reductions in subsidies could bring more equity to the distribution of transportation benefits among employees.

Employer policies on assigning free parking can vary widely. Transportation planners should study these policies at a disaggregate level to understand the dynamics within job classifications and among employer type and size categories.

Response to Employee Surveys

Employee responses in the baseline survey generally corroborate the information reported by the employers. Re-

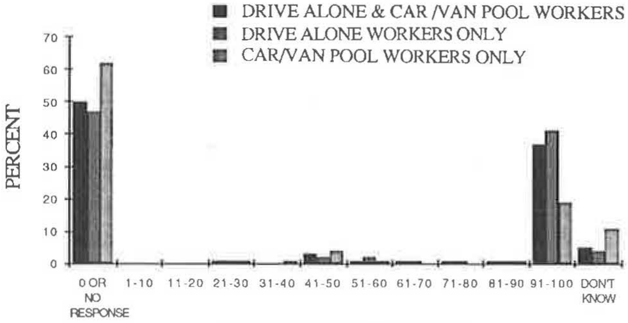

FIGURE 3 Los Angeles CBD employee travel survey: Questions 16 and 35—parking reimbursement (*5*).

sponses to questions concerning parking reimbursement indicate that 37 percent of employees are reimbursed for 91 to 100 percent of their cost (Figure 3). The rate of nonresponse was 50 percent for this question.

Nonresponse was a problem in many of the questions about employee parking cost or reimbursement level. It may be that employees do not know their true parking costs or subsidy. Further research is needed to determine the reason for the high level of nonresponse.

One surprising finding is that a greater percentage of drive-alone workers reported 91 to 100 percent parking cost reimbursement than did carpool or vanpool participants. (Among drive-alone workers, 84 percent knew their level of reimbursement; 70 percent of carpool or vanpool workers knew their level of reimbursement.) Ideally, incentives should favor those in carpools or vanpools. See Figure 3 for details.

There are two possible explanations for higher drive-alone parking reimbursement. First, the nonresponse rate for these questions was substantial, and the results may not be representative. Second, it may be that carpools and vanpools were formed by commuters in response to a lack of employer subsidy of parking cost.

The telephone survey of commuter attitudes provides some additional useful information about parking behavior. To reduce cost, the consultant based the sample for this survey on a 3-year-old data base. Therefore, some bias may exist in the results, because respondents were downtown employees with a tenure of at least 3 years. The survey took place in 1986.

Most respondents to the telephone survey (95 percent) arranged for parking on a monthly basis. Therefore, commuters do not make a day-to-day trade-off in terms of parking location, cost, and convenience. Second, 83 percent of respondents indicated that they had not changed their parking location in the last 12 months. Most of those who changed did so because of a job shift (60 percent). Only 22 percent of those who changed did so because of parking cost.

The picture that emerges from these data, when combined with the employer subsidy information, is of a parking market in which employers make the decisions about parking. Employees do not shop for parking, make trade-offs, or otherwise change their parking arrangements. They accept (or demand) subsidized spaces from employers.

Level of Drive-Alone Commuting

The baseline survey determined that drive-alone commuters represent 59.8 percent of total office commuters. The confidence interval is ±4.3 percent, at a 95 percent confidence level. Rideshare commuters represented 38.1 percent of the total ±4.7 percent (*5*). Table 1 gives a breakdown of the data for the study area, which included most of the office development in downtown Los Angeles.

The baseline survey was used to compare these results with those from a previous commuter mode survey conducted in 1981. It was found that drive-alone commuters represented 52.3 percent of all commuters (*7*). The 1981 study used a wider range of employment classifications than did the baseline survey.

Despite some differences in samples, the two sets of results suggest no decrease in drive-alone commuting. This is not a surprise, because no major transit improvements have been completed as of the more recent survey date, and gas prices are low. In addition, recent bus service cutbacks and fare increases have affected transit ridership. However, this may change. As congestion becomes more severe, the advantages of convenience and time inherent in driving alone to work may diminish.

No attempt is made here to develop a predictive model of mode choice using survey data. However, in disaggregate form, the baseline survey data can be used to examine those relationships. Suggestions are made in the sections

TABLE 1 LOS ANGELES CBD EMPLOYEE TRAVEL SURVEY: OFFICE WORKER RIDESHARING (*5*)

COMMUTE MODE	PROPORTION OF COMMUTERS	CONFIDENCE INTERVAL
DRIVE ALONE	59.8%	+/- 4.3%
WALK AND OTHER	2.1%	+/- 1.2%
RIDESHARE (TOTAL)	38.1%	+/- 4.7%
Carpool/Vanpool	3.1%	+/- 1.1%
Drove w/ > 1 Person	14.1%	+/- 2.4%
Bus/Train	20.9%	+/- 3.7%

that follow concerning policy implications and follow-up research.

IMPLICATIONS FOR PARKING POLICY

The findings of the surveys reflect conditions in downtown Los Angeles in the summer of 1986. The reader should exercise caution in drawing conclusions about other cities or employment centers from these results. The findings frame issues for subsequent investigations and replication efforts. Summarized below are comments on various policy issues in light of the initial findings of the surveys.

Parking Taxes

Many have proposed parking taxes as a way of reducing drive-alone commuting. The survey finding that most applies to this policy option is the extent of employer involvement in paying for parking. In many cases, the incidence of a parking tax would affect the employer, not the individual commuter. Therefore, predictions of commuter mode changes must take into account the likely action of employers in modifying their parking subsidies. Employers could pass the cost along, absorb the cost, shift subsidies to other modes, or relocate. Significant uncertainty exists regarding likely employer responses to such a policy. It is possible that many commuters would not be aware of any parking-tax-related increase in parking cost because they do not pay any of their parking cost now.

Parking Supply Restrictions

The survey responses suggest that policies restricting parking supply may affect employers more directly than employees. Employers are generally responsible for providing parking along with the job, and it is likely that employees will continue to demand parking spaces. In Los Angeles, jobs may be available in multiple employment centers, so some employers may have a difficult time attracting employees.

Parking supply restrictions can work if the public or private sector provides commute-mode alternatives when the parking supply is restricted. Therefore, transportation planners must develop parking management and other TDM measures in close cooperation with employers.

Transit Investments

Because of the prevalence of parking subsidies, rail transit planners must coordinate their improvements with revisions in parking policy. This coordination is difficult in Los Angeles because of the multiplicity of agencies with responsibility for transit and parking. However, ignoring these parking subsidies can seriously reduce transit ridership. Policies should be aimed at releasing funds used for parking subsidies and redirecting them into transit pass programs. The cost of a Southern California Rapid Transit District (SCRTD) monthly pass is half the median monthly parking fee. Again, it is up to the employer to shift incentives that influence commuter mode choice.

Peripheral or Off-Site Parking Strategies

Policy makers have proposed schemes to limit on-site permit parking and require the provision of peripheral intercept lots. A major question is whether commuters will accept the additional travel time and inconvenience to use such a system. The answer depends again on the level of involvement of the employer. Attempts to lure subsidized commuters directly to peripheral lots will almost surely fail. No amount of subsidy can overcome free or subsidized employer parking at or near the work site. However, because of the extent of the subsidy received by commuters, employers who move subsidized spaces to peripheral locations would likely find that commuters follow the subsidy.

SUGGESTED RESEARCH

The findings of the surveys suggest a number of areas for research in parking policy.

Replication of Study Findings

Similar surveys are needed in different cities and of different types of employment centers so that a broader base of knowledge on parking subsidies can be developed. Although transportation and land use conditions can vary substantially between cities, there may be a commonality in the way that employers make decisions about parking subsidies.

Suburban areas are also of interest, because free parking is much more prevalent there. As land values and densities rise in suburban areas, parking charges will be more frequent. The reactions of employers and commuters to these parking costs will likely have a major impact on mode-split trends in suburban areas.

Models

Planners need simple models to predict how alterations to parking policies will divert drive-alone commuters to other modes. Of course, such models must hold constant the other factors involved in mode-choice selection. The data from the baseline survey are a good source for further research in this area.

A few comments are appropriate concerning the modeling task. First, if modelers include parking price as an

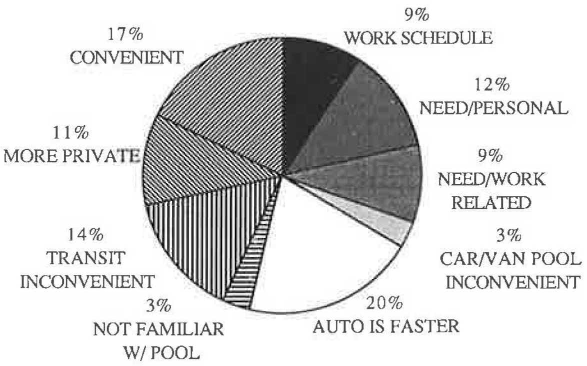

FIGURE 4 Los Angeles CBD employee travel survey: Question 36—most important reason for driving alone (*5*).

independent variable, it must be the after-subsidy price. Using surveys of market-rate parking prices would misspecify a model. Second, modelers need a technique for predicting the response of employers to changes in the parking cost and supply in order to have some certainty about employers' subsidies and the stability of the after-subsidy price over time.

An additional issue concerns the threshold levels at which either low or high parking prices become incentives or disincentives in commuter mode choice. It may not be possible to model commuter response to pricing changes using linear or transformed linear equations. There may be certain high and low thresholds where parking price is a determinant. Between these thresholds, commuters may be relatively indifferent to changes in parking price. The parking subsidies in downtown Los Angeles may be so great that parking costs are simply not a part of many commuters' mode-choice decision.

The baseline survey does not provide as much information in this area as would be desirable. Drive-alone commuters were asked why they chose that mode. Most respondents cited the speed and convenience of the automobile and the inconvenience of transit as the main reasons for driving alone to work (see Figure 4). However, the questionnaire did not list subsidized parking as a potential response—an oversight in the questionnaire design.

It is difficult to determine how many drive-alone commuters would have indicated that low parking prices are a factor in mode selection had that response category been included in the survey. One way to use the existing data would be to disaggregate the responses by level of subsidization to determine how the reasons for mode choice change with varying parking subsidy levels.

Employer Decision-Making Process Regarding Employee Benefits

The decision-making process of employers in evaluating subsidy programs is not well understood. Depending on the type of company, decision-making processes may vary widely. However, it is this process that is the key to altering the commuting patterns of employees. Public regulation and programs must recognize this process as central and find ways to affect it. For example, regulating developers without attention to eventual tenants will not yield good results. Personnel departments usually make the recommendations about parking subsidies, but there is evidence of increasing upper-management involvement in these decisions.

The Wagner and Schueftan survey of employer attitudes toward transportation for employees is a key first step in identifying how employers view their transportation benefits (*8*). Planners need more information on how to affect employer policies.

Parking and Congestion Pricing Mechanisms

Employers and building owners usually resist attempts to change their parking policies. Public-sector officials are reluctant to change parking policies and perceive high political risk. These difficulties exist when the mechanism under consideration is public regulation. There are practical and legal difficulties in regulating parking subsidies offered by employers to employees. Development agreements offer the most potential, but enforcement problems are significant.

More study is needed on the use of mechanisms that price the amount of congestion generated by a development and permit buying and selling of congestion rights. Building owners and employers could then reap economic benefits by reducing drive-alone commuting, using rideshare incentives and drive-alone parking disincentives as appropriate. Altering parking price policies would likely be a frequently used strategy. This "pricing" approach offers more potential than regulation, which may be met with resistance.

CONCLUSIONS

Two commuter mode surveys were recently conducted in downtown Los Angeles. They indicate that employers strongly subsidize employee parking. These subsidies mean that very few employees shop independently for parking, and few make decisions based on true costs. Despite the substantial cost of these subsidies to employers, there is no evidence that their use is diminishing.

Other studies have shown the effect of parking subsidies on mode choice. Employers must reduce these subsidies if investments in transit and rideshare incentives are to succeed. As land values and congestion levels continue to grow, the opportunity cost of this misallocation of employers' subsidies is becoming more apparent.

Solutions to this problem lie with changing employer benefit policies. Programs that focus on the commuter alone miss the target. Yet knowledge of how to change employer policies is limited. One approach that some cities have taken is regulation of employers (for rideshare participation). The success of these efforts will depend on how well employers' decision-making processes regarding employee benefit packages are understood—how employers decide on benefits and how they can be persuaded or induced to alter them.

ACKNOWLEDGMENTS

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REFERENCES

1. D. Shoup. *Free Parking as a Transportation Problem.* U.S. Department of Transportation, 1980.
2. J. DiRenzo, B. Cima, and E. Barber. *Parking Management Tactics,* Volume 3: *Reference Guide.* U.S. Department of Transportation, 1981.
3. *Los Angeles Coastal Corridor Specific Plan Summary.* Department of Planning, City of Los Angeles, Calif., 1985.
4. P. Roche and R. Willson. Ridesharing Requirements in Downtown Los Angeles: Achieving Private-Sector Commitments. In *Transportation Research Record 1082,* TRB, National Research Council, Washington, D.C., 1986, pp. 1–6.
5. Barton-Aschman Associates, Inc.; Recht Hausrath & Associates. *Los Angeles CBD Employer-Employee Baseline Travel Survey.* Los Angeles Community Redevelopment Agency, Los Angeles, Calif., 1987.
6. Kotin, Regan Mouchly, Inc. *Commuter Attitudes Regarding Peripheral Parking Study in Downtown Los Angeles.* Los Angeles Community Redevelopment Agency, Los Angeles, Calif., 1986.
7. Wilbur Smith and Associates. *Central City Parking Study.* Traffic Department, City of Los Angeles, Calif., 1974.
8. D. Wagner and O. Schueftan. *Employer Involvement in Employee Transportation.* UMTA, U.S. Department of Transportation, 1985.

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Arterial Priority Option for the TRANSYT-7F Traffic-Signal-Timing Program

M. JOHN MOSKALUK AND PETER S. PARSONSON

The objective of this research was to modify TRANSYT-7F so that arterial priority can be increased and minor-movement performance degradation can be controlled. The product is known as TRANSYT-7F with Arterial Priority Option (APO). TRANSYT-7F "globally" minimizes overall stops and delay to all vehicles. This is satisfactory for a grid network on which good traffic performance is desired equally for every street. However, it is unsatisfactory for arterials on which progression for the through movement typically is considered much more important than minimizing stops and delay for left-turning and side-street motorists. In the United States, TRANSYT-7F is widely perceived as unsatisfactory for arterial signal timing. TRANSYT-7F with APO modifies the iterative-search process to give priority to the arterial. APO changes the optimization process, not the traffic flow model. In general, the user specifies which links are to receive priority and the degree of saturation for the minor movements (nonpriority links). The performance index (PI) equation is formulated to minimize stops and delay for only the priority links. The degree of saturation specified by the user for the minor movements is used to control the performance degradation to acceptable levels. The results of a program run may be used to make changes to the list of priority links and to the required degree of saturation of one or more nonpriority links on the basis of the engineer's judgment. APO is thus user interactive; the engineer retains control over the optimization and can tailor it to local conditions.

The objective of this research was to modify TRANSYT-7F so that arterial priority can be increased and minor-movement performance degradation can be controlled. The revised signal timing program is known as TRANSYT-7F with Arterial Priority Option (APO).

TRANSYT-7F is ideally matched to the development of grid-system signal-timing plans because of the equal priority given to all motorists. For an arterial, the traffic engineer and the motorist want timing plans that give priority to the through arterial movements. They want arterial progression even if minor movements must experience more delay and stops. Because TRANSYT-7F is widely accepted and used, what has been needed is a methodology that permits the user to control the amount of priority that is allocated to the arterial. To accomplish this objective, the user of APO is permitted to specify the minor-movement degree of saturation within a range so that this value becomes the criterion on which to degrade performance. As the minor movement is degraded, the arterial will be given more priority through the increase of split times and the adjustment of offsets; thus, the arterial timing plan will provide smoother progression.

PROCEDURE

After several false starts in the development of a procedure to accomplish arterial-priority timing, it was realized that modification of the existing TRANSYT-7F software was necessary. In this section the development of the APO is described.

The source code for the existing version of TRANSYT-7F was obtained from Gary Euler of FHWA. It was supplied on a floppy disk and occupied 230 kilobytes (K) of storage. The source code has 13 modules and must be compiled and linked using a FORTRAN 77 compiler, such as that of Microsoft (*1*). Euler also furnished a descriptive report (*2*) of the source code structure with names and meanings of variables.

For user control of procedures giving more priority to an arterial, several measures of effectiveness were considered. It was concluded that the degree of saturation was the most appropriate measure of effectiveness because it is directly related to delay. Thus, as the arterial priority is increased, the degree of saturation for the minor movement will increase because of increasing delay. As the delay increases for minor movement, vehicular stops will also increase, because TRANSYT-7F computes stops as a function of the cyclic flow profile.

TRANSYT-7F with APO changes the optimization process, not the traffic flow models. In general, the user specifies which links are to receive priority and the degree of saturation for the minor movements (nonpriority links). The performance index (PI) is formulated so that it uses only the priority links in the calculation. No longer is a global PI calculated to determine the optimum solution. For each nonpriority link, TRANSYT-7F with APO sets a ±5 percent range for the specified degree of saturation. At each intersection, each nonpriority link is checked for degree of saturation during the iterative search process.

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TABLE 1 CARD TYPE 31: PRIORITY LINK LIST CARD

Field	Column	Description	Range
1	1	"31"	Optional
2-16	10-80	Link numbers which have priority	Link numbers

When the computed value for the degree of saturation on the nonpriority link is within the range, the iterative search is stopped and begun again at the next intersection.

Three areas of the source code—user input, optimization model, and output—were changed. Modifications are described as follows.

Changes to User Input

The input format for the priority data was structured similar to TRANSYT's existing format. Two arterial priority cards were designed. Card type 31 designates which links are to be included in the priority scheme. Card type 32 indicates which links do not have priority and their associated desired degree of saturation. Both card types have a straightforward coding format. Table 1 shows the format for card type 31. Card type 32 is shown in Table 2.

Changes to Optimization Model

TRANSYT-7F with APO continues to use the iterative-search process as described in the previous section but interrupts the iterative process on each pass so that the nonpriority-link degree of saturation can be evaluated. Formulation of the PI includes only those links that the user indicated on card type 31. Therefore, the modified version does not calculate a global PI to determine the optimum solution. Instead, it calculates a PI designated only by priority links.

In summary, there are two ways to halt the modified search technique of TRANSYT-7F with APO. When the new PI is greater than the old PI, subroutine hill-climb decides that an optimum solution has been found and goes to the next intersection. This is exactly the same as in the existing version of TRANSYT-7F. With APO the nonpriority-link traffic flow is degraded to be within the range of the degree of saturation as assigned by the user, the iterative-search technique is stopped, and the subroutine hill-climb goes to the next intersection.

Evaluation of the degree of saturation provides the user with a great deal of flexibility and control over the signal-timing plan that is developed by TRANSYT-7F. The APO allows the user to interact with the optimization process.

Changes to Output

A summary performance table by link type was added to the existing TRANSYT-7F output tables. The user can

TABLE 2 CARD TYPE 32: NONPRIORITY-LINK DEGREE OF SATURATION

Field	Column	Description	Range
1	1	"32"	Optional
	**************	Alternative 1*************	
2	5	All links not listed on card type "31" have no priority	-999
3	10	Degree of Saturation	10 to 150
	**************	Alternative 2 ************	
2	5	Non-priority link	Link #
3	10	Degree of Saturation	10 to 150
4	15	Non-priority link	Link #
5	20	Degree of Saturation	10 to 150
	Alternate link numbers and degree of saturation		

apply this table in conjunction with present tables to evaluate the effects of selecting TRANSYT-7F with APO.

FINDINGS

A section of Tenth Street in Atlanta, Georgia, was selected to test TRANSYT-7F with APO. Tenth Street is an east-west arterial located just to the north of the Atlanta central business district near the Georgia Institute of Technology campus. The test section is from Fowler Street on the west to West Peachtree Street on the east. There are five signalized intersections in this 1,765-ft section of roadway.

Initial conditions for Tenth Street included the following:

- Traffic flow and network data were coded as discussed in the previous section.
- The signal phasing used was that which existed at the time the data were collected. The existing phasing for each intersection was
  - Intersection 1: Tenth and Fowler streets—two-phase operation,
  - Intersection 2: Tenth Street and Techwood Drive—three-phase with a leading westbound left turn,
  - Intersection 3: Tenth Street and Techwood Drive—three-phase with a leading eastbound left turn,
  - Intersection 4: Tenth and Spring streets—three-phase with a leading eastbound left turn,
  - Intersection 5: Tenth and West Peachtree streets—three-phase with a leading westbound left turn.
- All clearance interval times were set to 4 sec and were fixed so that TRANSYT-7F did not vary these intervals.
- No pedestrian time was coded; the minimum time for each variable (green) interval was set at 1 sec.
- A 60-sec cycle was used for this example. Several runs of TRANSYT-7F using the cycle-selection feature of the program indicated that this cycle was appropriate.

The initial conditions for all TRANSYT-7F runs were the same.

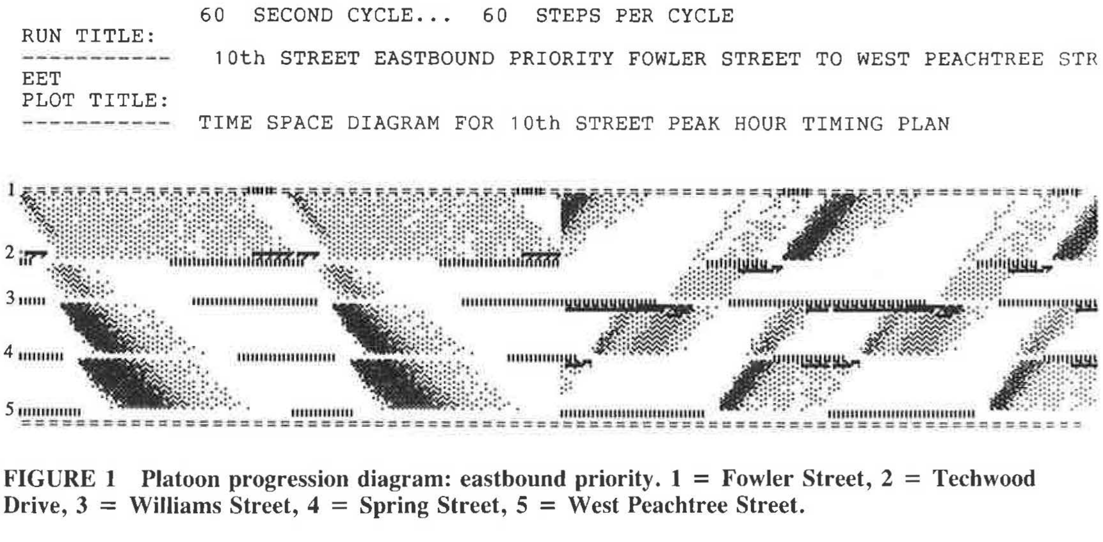
To demonstrate user control and flexibility of TRANSYT-7F with APO, a series of computer runs to simulate traffic flow on Tenth Street was performed. For purposes of brevity and illustration, only two examples are presented.

TRANSYT-7F with APO was used to give priority to eastbound Tenth Street. The links selected for priority were 113, 213, 313, 413, and 513. From an evaluation of the output in comparison with TRANSYT-7F without APO, the following observations were made:

- The eastbound PI was reduced to 6.25 vehicle-hr/hr from the base timing plan of 16.23 vehicle-hr/hr. This presented a 61 percent reduction in PI. Eastbound delay was reduced from 7.20 to 2.66 vehicle-hr/hr, or 63 percent. Stops were reduced from 1,298.94 to 530.62 vehicles/hr, or 59 percent.
- Degree of saturation on the nonpriority links increased.
- The platoon-progression diagram (Figure 1) indicated that priority was indeed given to the eastbound arterial on Tenth Street.

To further demonstrate the flexibility and user control of TRANSYT-7F with APO, arterial priority was given to both eastbound and westbound movements concurrently. The priority links for this run were 113, 213, 313, 413, 513, 414, 214, 314, and 114. The results were as follows:

- Progression was possible in both directions (Figure 2).
- Global PI was increased to 121.17 from 91.51 for the base timing plan, an increase of 32 percent.
- Both directions of the arterial have less delay and fewer stops when compared with the base timing plan. Eastbound PI was reduced by 24 percent and westbound PI by 39 percent.
- Total delay for the eastbound arterial was reduced by 41 percent, from 7.20 to 4.25 vehicle-hr/hr. In the west-



```
                 60  SECOND CYCLE...  60  STEPS PER CYCLE
RUN TITLE:
-----------       10th STREET EASTBOUND PRIORITY FOWLER STREET TO WEST PEACHTREE STR
EET
PLOT TITLE:
-----------      TIME SPACE DIAGRAM FOR 10th STREET PEAK HOUR TIMING PLAN
```

FIGURE 1 Platoon progression diagram: eastbound priority. 1 = Fowler Street, 2 = Techwood Drive, 3 = Williams Street, 4 = Spring Street, 5 = West Peachtree Street.

```
                   60  SECOND CYCLE...  60  STEPS PER CYCLE
RUN TITLE:
-----------         10th STREET EASTBOUND AND WESTBOUND PRIORITY

PLOT TITLE:
-----------        TIME SPACE DIAGRAM FOR 10th STREET PEAK HOUR TIMING PLAN
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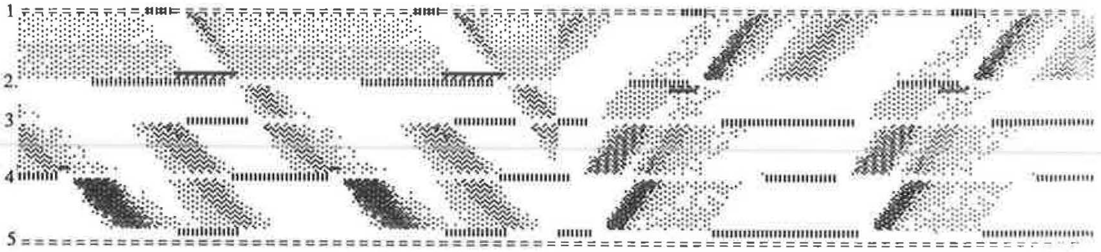

FIGURE 2 Platoon progression diagram: eastbound and westbound priority. (Streets are identified in Figure 1.)

bound direction, total delay was reduced from 4.93 to 2.93 vehicle-hr/hr, or 41 percent.

- Eastbound stops decreased from 1,298.94 to 1,161.84 vehicles/hr, or 11 percent. In the westbound direction, stops were reduced from 931.82 to 579.36 vehicles/hr, a reduction of 38 percent.
- Minor movements have more delay and stops when compared with the same movements in the base timing plan. The total global PI for the northbound and southbound links is 80.74, or 67 percent of the global PI.

CONCLUSIONS

The objective of this research was to modify TRANSYT-7F so that arterial priority can be increased and minor-movement performance degradation can be controlled. TRANSYT-7F with APO accomplishes this objective, as has been demonstrated here for Tenth Street in Atlanta.

This research led to the following conclusions:

1. User selection of APO gives a reduction of delay and stops for the arterial links and a smoother overall arterial progression.
2. Minor-movement performance degradation is controlled by the user specification of degree of saturation for the nonpriority links.
3. On examining the results of an iteration, the user may apply judgment to make changes to the list of priority links and to the required degree of saturation of one or more nonpriority links. APO is thus user interactive; the engineer retains control over the optimization and can tailor it to local conditions.
4. A particularly desirable feature of TRANSYT-7F with APO is the continued use of delay and stops in the PI formulation to find optimum signal-timing plans.

From this research, it is concluded that the concept of specifying the degree of saturation on the nonpriority links proved to be successful in controlling arterial priority. APO allows the optimization process to be user interactive and flexible. The user has firm control over the relative priority given to the various movements in an arterial system.

REFERENCES

1. *Microsoft FORTRAN 86, Version 3.2.* Microsoft Corporation, Bellevue, Wash., 1986.
2. *Traffic Network Study Tool—Version 7, Federal: TRANSYT-7F (Release 4) Software Summary.* FHWA, U.S. Department of Transportation, 1984.

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MAXBAND-86: Program for Optimizing Left-Turn Phase Sequence in Multiarterial Closed Networks

EDMOND C-P. CHANG, STEPHEN L. COHEN, CHARLES LIU, NADEEM A. CHAUDHARY, AND CARROLL MESSER

Four variables are available to the traffic engineer that can be used to optimize the flow of traffic in signalized urban networks. Three of these—green phase time, offset, and cycle length—are well known, and a number of computer programs are available to determine them. A fourth variable, left-turn phase sequence, is less well known and can be computed only for arterial networks by existing software. Recognizing that the left-turn phase sequence might be an important variable in multiarterial closed networks, the Federal Highway Administration (FHWA) contracted with Texas Transportation Institute (TTI) to extend the MAXBAND program, which was restricted to single arterials and triangular networks, to such general networks. The extensions made to the MAXBAND program resulted in MAXBAND 86; these extensions are described in this paper. The application of MAXBAND 86 to a study of the effect of the left-turn phase sequence in 10 multiarterial closed networks is described also. The study included comparison of MAXBAND-produced timing plans with and without phase sequence optimization and an analysis of the effects of using phase sequence patterns given by MAXBAND in the TRANSYT program. The results indicate that optimization of the phase sequence can often provide a substantial benefit in terms of reduced delay and stops.

Traffic engineers have long recognized that traffic signals located within the downtown network should be coordinated to provide orderly movement of vehicular traffic. The need for network signal timing is to keep the traffic moving by the timely display of green signals to the platoons traveling through the arterial signal networks.

In determining optimal signal timing plans for signalized networks, the traffic engineer needs to incorporate the following decision variables:

1. Offset,
2. Green phase time,
3. Cycle length, and
4. Left-turn phase sequence.

A number of computer programs have been developed to assist the traffic engineer in obtaining signal timing plans for urban traffic arterials and networks. None of these programs incorporate all four decision variables. Delay-based programs such as TRANSYT (*1*) and SIGOP II (*2*) select offsets, green times, and cycle lengths, whereas bandwidth programs such as MAXBAND (*3*) select offsets, cycle lengths, and left-turn phase sequences. The modification of these programs to include all four of the above-mentioned decision variables is either impossible or computationally infeasible. Cohen and Mekemson explored the possibility of using MAXBAND and TRANSYT-7F sequentially (*4*). In this approach, MAXBAND is used to provide an initial timing plan, including an optimized phase sequence for TRANSYT, which then proceeds to adjust the offsets and green times to minimize a weighted combination of delay and stops. The results of this approach indicate that optimizing the left-turn phase sequence can result in delay and stop reductions on multiphase arterial signal systems.

The original MAXBAND program was capable of optimizing signal timing plans only for arterials and those networks that are composed of three arterials forming a single triangular loop. Thus, the approach of using maximum-bandwidth and minimum-delay strategies sequentially cannot be readily extended to general grid traffic networks.

APPROACH: MAXBAND 86

In order to provide the capability of optimizing the left-turn phase sequence in general multiarterial closed networks, the Federal Highway Administration (FHWA) decided to generalize the limited MAXBAND network capability to such networks. This work was performed by the Texas Transportation Institute under contract to FHWA. In addition, several other modifications were added to the model to improve its user-friendliness. These include a new signal timing summary table and an algorithm to automatically generate the network closure constraints for multiarterial closed networks. The MAXBAND 86 program and a study in which the effect of

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optimizing the left-turn phase sequence in networks was examined for the first time are described in this paper.

SYSTEM OVERVIEW

MAXBAND 86 consists of a main program and four major submodules, namely, INPUT, MATGEN, MPCODE, and OUTPUT. The main program acts to control the execution of each of these submodules. It communicates with the submodules by means of an argument list of CALL statements. The function of each submodule is explained in the following paragraph.

The INPUT module controls the reading of data, does error checking, and performs calculations, which include using weights given by the user to obtain bandwidth ratios and objective function coefficients. The MATGEN module formulates the problem as a mixed-integer linear program and writes the formulation on a file. At this point, module MPCODE reads the file written by module MATGEN and begins the optimization process. At the termination of MPCODE, control is transferred to the OUTPUT module, which writes the solution report.

The overall structure of the original MAXBAND program remained unchanged during its evolution to MAXBAND 86. However, the MPCODE module is the only one that was not substantially revised. Changes in each of the modules range in degree and character. These changes include expansion of variable dimensions, addition of new variables, addition of new subroutines, and modification of subroutines to handle problems of a more general nature. A major addition was subroutine LGEN and its supporting subroutines. Their purpose is to identify the independent set of loops and to store information regarding loop geometry in a form used by the MATGEN module to write the network closure constraints.

The design of the MAXBAND data input structure for network problems was such that the user ended by providing some duplicate information. Further, the program did not check whether these duplicate data were consistent or not. This problem could have been eliminated by modifying the structure of input data records. However, because the objective of this research was to retain the existing input data formats so that already coded problems could be run without major changes, this was not done. Instead, several subroutines were added to the module that reads data. The purpose of these subroutines is twofold: first, to provide the capability for extensive error checking of duplicate or inconsistent data, and second, to give the user an option by which the duplicate data can be eliminated.

DESIGN ASSUMPTIONS

In order to provide traffic signal timing methodology for general networks, there was a need to define the scope of networks that could be optimized by MAXBAND 86. The following design assumptions were used to specify cases to be considered by the program.

1. The network must be completely connected; that is, there can be no disjoint arterials or subnetworks. (Note that these latter cases may be treated by solving each of the independent subsystems and then combining the results.)
2. No more than two arterials may compose an intersection; that is, there are no five-way or six-way intersections. (The green-split calculations do not currently permit this more complex analysis.) Here an arterial consists of any one-way or two-way linear road segment with two or more signals, and a network is made up of one or more such arterials.
3. The network may have a maximum of 36 independent loops, with no more than six arterials forming the boundaries of a loop.

The prior version of MAXBAND allowed the user to optionally analyze a portion of an arterial for which data were read. This feature is retained for arterial problems. However, the user cannot do this for a network problem, because in this case there exists the possibility of creating a disconnected network.

MAXBAND 86 NETWORK FORMULATION

The network problem formulation draws on work by Little and Kelson (*5–7*) and is presented in the MAXBAND 86 research reports (*8–10*). The problem formulation consists of the following major components:

1. The objective function, a weighted combination of one-way bands mathematically expressed as

$$\text{maximize} \sum_{i=1}^{n} c_i b_i + c_i b_i$$

where n is the number of arterials in the network, c_i $(\overline{c_i})$ is the outbound (inbound) direction objective function weight for the ith arterial, and $b_i(\overline{b_i})$ is the outbound (inbound) band for the ith arterial.
2. Independent formulations of each arterial in the network.
3. Optional constraints to control the relative importance of arterials to each other.
4. A set of network closure constraints, which consists of a constraint for each independent closed loop in the network. The purpose of these constraints is to combine the individual arterial formulations by ensuring that the sum of the offsets in a loop is equal to an integral multiplier of the cycle length. A major contribution of this research was the derivation of an algorithm to determine the set of independent loops in the network, described in the next section.

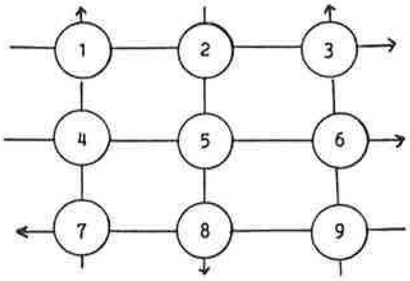
MAXBAND'S LOOP-GENERATION ALGORITHM

The network progression problem requires the identification of the network connectivity in order to provide network closure constraints for optimization. Identification of the independent loops allows the MAXBAND 86 program to simplify the network topology and use the information to write the loop-closure constraints for optimization. For example, there are $(l - n + 1)$ fundamental loops in a network, where n is the number of nodes and l is the number of links in that network. The loop identification algorithm allows the program to develop the simplest $(l - n + 1)$ equations defining the complete network topology. Several algorithms have been developed to find this fundamental set of loops (*11–13*). A modified version of Paton's algorithm (*11*) is used in MAXBAND 86 because it is computationally efficient and requires less storage space in the computer than other algorithms. The differences between the original and the modified algorithms are as follows:

1. As opposed to Paton's original algorithm, the modified algorithm uses the node with the most links incident to it as the root of the spanning tree. This results in a simpler loop set in most cases.
2. The construction of the tree and cotree is completed before tracing of the loops is begun.
3. The links in the cotree are examined and if possible the loops are further reduced to simpler ones.

The reason for placing more emphasis on finding simpler loops is that their coefficients in the formulation matrix will occupy less space.

As shown in Figure 1, the modified Paton algorithm requires a node adjacency matrix as part of the input data file. MAXBAND 86 creates this matrix from the unique node identification numbers that the user must supply. These identification numbers can be any alphanumeric string up to five characters long. Starting from 1, MAXBAND assigns a sequence number to each node identification number. It also identifies arterials intersecting at a particular node and their corresponding signal numbers. All the network information is stored in a logical table for easy reference.



$$A = \begin{array}{c|ccccccccc|} & 1 & 2 & 3 & 4 & 5 & 6 & 7 & 8 & 9 \\ 1 & & 1 & & 1 & & & & & \\ 2 & 1 & & 1 & & 1 & & & & \\ 3 & & 1 & & & & 1 & & & \\ 4 & 1 & & & & 1 & & 1 & & \\ 5 & & & 1 & & 1 & & 1 & & 1 \\ 6 & & & 1 & & 1 & & & & 1 \\ 7 & & & & 1 & & & & 1 & \\ 8 & & & & & 1 & & 1 & & 1 \\ 9 & & & & & & 1 & & 1 & \end{array}$$

FIGURE 1 Application of modified Paton algorithm. (Note: orientation of arteries has no effect on the adjacency matrix.)

CAUTIONARY NOTE

The MAXBAND 86 program retains the Mixed Integer Linear Program (MILP) package MPCODE that was used in the previous versions of the program. This package solves the MILP problem, which forms the basis of MAXBAND. This can lead to severe computational problems for larger closed networks, because the resulting optimization problem will become very complex.

For example, MAXBAND 86 may be given problems that, when formulated, can result in a linear integer programming problem that has more than 1,000 constraints and variables and close to 350 discrete variables for a signal network of 50 signalized intersections. Because it was not anticipated that the existing MPCODE optimization module could handle optimization problems of this size, smaller array dimensions were set in the MPCODE. Under the existing configuration, the problems that the MPCODE can theoretically handle now may have up to 700 variables, 990 constraints, and 200 discrete variables. The research team recognized that the largest deficiency of MAXBAND 86 is the efficiency of the optimization module, and it is unclear whether the existing optimization technique as implemented in the current MAXBAND 86 can find a global optimum solution to the problem of a large signal network.

APPLICATION: LEFT-TURN PHASE SEQUENCE IN NETWORKS

As has previously been mentioned, the motivating factor for performing this work was to provide the capability for optimizing the left-turn phase sequence in any network with multiphase signals. Thus, when the program became available, a set of experiments was performed on 10 real-world networks for which data were available. Descriptions of these networks are given in Table 1. In most cases, the existing signal design was not available. The available data consisted of input streams for the TRANSYT-7F program, which included experimental signal-phasing designs that did not necessarily have any relationship to the phasing designs at the actual sites. However, all other traffic and geometric data reflected actual site conditions. Therefore, in the signal phasing for this set of experiments, all approaches that had a left-turn lane or turning pocket were assigned an exclusive left-turn phase regardless of whether such a phase was warranted. However, very short mini-

TABLE 1 NETWORK DESCRIPTIONS

Network	Signalized Intersections	Left Turn Phases	Cycle Lengths	Signal Spacing (Feet)	Location
Daytona Beach	12	20	120	600-777	Florida
Odgen	13	12	80	381-776	Utah
Owosso	16	23	80	358-3600	Michigan
Walnut Creek	13	21	100	200-1720	California
Ann Arbor	14	17	100	321-820	Michigan
Memphis	17	12	100	393-799	Tennessee
Bay City	16	20	100	478-3979	Michigan
Houston	13	13	100	450-2700	Texas
Los Angeles	15	15	100	746-2471	California
San Ramon	17	19	120	510-4900	California

mum greens (8 sec) were assigned to the left-turn phases, so any effect due to unwarranted phases was small. No other changes were made to the input data. In particular, no left-turn volumes were increased, because it was determined that such modifications would result in findings that would be biased in favor of phase-sequence optimization. This is because increasing left-turn volumes would result in longer left-turn phases, which would result in larger increases in bandwidth produced by optimizing the phase sequence.

Two sets of experiments were performed:

1. In the first set, the MAXBAND 86 program was executed to provide timing plans for all 10 networks both with and without phase-sequence optimization (no leading lefts had phase-sequence optimization). The NETSIM program was then used to simulate the network performance using both sets of MAXBAND 86 timing plans.
2. In the second set, the MAXBAND 86 timing plans from the first set of experiments were used as starting solutions for the TRANSYT-7F program, which then produced minimum delay/stop solutions. The NETSIM program was then used to simulate the network performance using both sets of TRANSYT-7F timing plans.

GENERAL REMARKS

Before discussion of the results, the following comments should be made:

1. The NETSIM model is a stochastic microscopic model that uses a sequence of randomly generated numbers to assign values to random variables such as speed, queue discharge headway, start-up delay, and left-turn gap acceptance. For this reason, estimates of measures of effectiveness (MOEs) such as delay and stops will have a certain amount of variability depending on the particular sequence of random numbers used. Past experience with the model on undersaturated networks of comparable size to the ones used in this work has shown that this variability is about 3½ percent. This means that when different timing plans are compared for the same network, a difference of 4 percent is probably statistically significant. A review of the 15- and 30-min cumulative statistics for the 10 networks studied indicated that the network statistics were indeed stable, which implies that the networks were undersaturated.
2. The cycle lengths were held fixed and are representative of cycle lengths used for typical multiphase operation.
3. The external links were not included in the Experiment 1 NETSIM runs because MAXBAND calculates a fixed deterministic green time for each movement (not phase), and all the benefits derived from improved progression accrue to the internal links. Thus delay on the external links will be independent of the phase-sequence patterns chosen. However, in the case of TRANSYT, it is not possible to hold the green time fixed for movements on external links without holding all green times fixed. Therefore, the external links were included for the Experiment 2 TRANSYT and NETSIM runs, so TRANSYT and MAXBAND timing plans are not comparable.
4. Four signal cycles were used as the "fill time" for each NETSIM run. One 30-min simulation run was made. Thus, as mentioned in the first item in this list, differences of less than 4 percent are not significant.
5. All signals were simulated as fixed time (as is usually the case for closed networks), and all left-turn movements from an exclusive lane were fully protected.

TABLE 2 MAXBAND BEFORE-AND-AFTER RESULTS

Arterial	Total[1] Band-Width Before	Total Band-Width After	% Change	NETSIM[2] Delay Before	NETSIM Delay After	% Change	NETSIM[3] Stops Before	NETSIM Stops After	% Change
Daytona	1.57	2.48	+58	84.4	56.7	-34	1.70	1.30	-23
Odgen	2.56	3.08	+20	46.2	39.9	-14	1.73	1.51	-13
Owosso	3.99	4.20	+ 5	55.0	53.2	- 3	1.44	1.40	- 3
Walnut Creek	2.09	2.77	+32	70.1	61.2	-13	1.72	1.55	-10
Ann Arbor	3.29	3.70	+12	44.2	35.0	-21	1.22	1.07	-12
Memphis	2.98	3.36	+12	35.2	30.9	-12	1.15	0.90	-22
Bay City	2.88	3.57	+23	82.2	74.0	-10	1.75	1.63	-12
Houston	2.44	2.82	+15	78.7	70.1	-11	1.80	1.58	-12
Los Angeles	3.03	3.61	+19	66.4	60.6	- 9	1.45	1.33	- 8
San Ramon	1.88	2.43	+29	115.0	108.2	- 6	2.12	2.08	- 2

1. Fraction of Cycle, Sum of All Bands
2. Seconds/Vehicle
3. Stops/Vehicle

RESULTS

The results of Experiment 1 (Table 2) show that in most of the networks substantial reductions in delay, stops, or both were achieved as a result of optimizing the phase sequence.

The results of Experiment 2 (Table 3) show that, in many cases, the improvements due to phase-sequence optimization appear smaller. In part, this is because the results have been "watered down" by the presence of the external links, which increase the total delay both before and after Experiment 2 (without the Experiment 1 activities).

DISCUSSION

It should be pointed out that the experiments performed here were limited to the examination of whether phase-sequence optimization using a bandwidth-based program such as MAXBAND 86 had potential for producing signal-timing plans that would, if implemented, result in lower values for delay and stops. Both MAXBAND 86 and TRANSYT-7F were used in a straightforward fashion, with no attempt to perform a deeper analysis of the problem. The results indicate that, given the limited purposes of these experiments, left-turn phase-sequence optimization has at least the potential to provide more effective signal-timing plans in networks with multiphase signal operations.

Conduct of these experiments uncovered a number of issues that were beyond the scope of this study but that could have had an important effect on the results.

1. One issue was bandwidth weighting in MAXBAND. In these experiments, equal directional bandwidth on individual arterials was used. Previous studies have shown that directional weighting, especially where there are unequal through greens, can significantly affect delay and stops (*14*).
2. Another issue was multiple solutions in MAXBAND. Although MAXBAND produces a global optimum, the experience with the 10 networks used here indicates that usually a number of solutions are found that have the same bandwidth to four or five decimal places. Thus, there is no practical difference among these solutions in terms of total bandwidth, but some may, for various reasons, give better performance in terms of delay and stops. It should be noted that this problem has previously been pointed out by Baass (*15,16*) with respect to single arterials. However, the network problem differs from the single-arterial problem as follows:
    a. For single arterials, the multiple solutions indicated by Baass are due to different combinations of cycle length and speed.
    b. For multiarterial networks, the multiple solutions occur for constant cycle length and speed and are due to the different possible ways in which the total bandwidth available in the network is divided among the arterials that make up the network.

TABLE 3 TRANSYT BEFORE-AND-AFTER RESULTS

Network	TRANSYT PI Before	TRANSYT PI After	% Change	NETSIM Delay Before	NETSIM Delay After	% Change	NETSIM Stops Before	NETSIM Stops After	% Change
Daytona	186.	165.	-11	96.5	79.3	-18	1.99	1.79	-10
Odgen	81.5	75.7	- 7	56.4	50.0	-11	2.08	1.89	- 9
Owosso	130.	126.	- 3	56.5	57.6	+ 2	1.59	1.57	- 1
Walnut Creek	216.	202.	- 6	92.8	76.3	-18	2.52	2.05	-19
Ann Arbor	86.4	85.7	- 1	54.5	55.4	+ 2	1.61	1.58	- 2
Memphis	83.2	83.8	0	52.4	50.2	- 4	1.61	1.42	-12
Bay City	184.	183.	- 3	91.9	91.6	0	2.05	2.03	- 2
Houston	234.	235.	0	96.0	89.0	- 7	2.13	2.17	+ 2
Los Angeles	210.	201.	- 4	83.5	82.8	- 1	1.82	1.79	- 3
San Ramon	155.	147.	- 5	120.9	117.6	- 3	2.36	2.35	0

The multiple-solutions problem will probably have a greater impact when phase sequence is optimized, if only because of the increased number of integer variables and hence possible solutions due to the optimization.

Preliminary indications are that the major causes of differences in delay and stops between solutions having the same bandwidth are as follows:

1. For a given solution, the position of the bands on some of the arterials relative to the start or end of the green time may cause parts of platoons to be stopped at certain intersections on those arterials.
2. The result of solutions for a network is usually that most of the arterials achieve virtually the entire amount of bandwidth that they would have received if optimized separately. A few (usually one or two) receive substantially less than the bandwidth they would have received if optimized separately. This compromise is due to requirements of the network closure constraints. For this reason, many of the near-optimal solutions differ only in terms of which arterials are degraded. Thus, if in one solution a minor arterial is degraded while in another solution a major arterial is degraded, one would expect the former solution to perform better in terms of delay and stops than the latter.

CONCLUSION

From the results of this study, it can be concluded that optimizing the left-turn phase sequence in multiarterial closed networks has potential for improving the performance of signal-timing plans, but that further research, such as that described in the Results section, is required.

REFERENCES

1. C. Wallace, K. G. Courage, D. P. Reaves, G. W. Shoene, and G. W. Euler. *TRANSYT-7F Traffic Network Study Tool User's Manual.* FHWA, U.S. Department of Transportation, Feb. 1983.
2. D. I. Robertson. *TRANSYT: A Traffic Network Tool.* TRRL Report 253. U.K. Transport and Road Research Laboratory, Crowthorne, Berkshire, England, 1969.
3. E. B. Lieberman and J. L. Woo. SIGOP II: A New Computer Program for Calculating Optimal Timing Patterns. In *Transportation Research Record 596,* TRB, National Research Council, Washington, D.C., 1976, pp. 16–21.
4. S. L. Cohen and J. Mekemson. Optimization of Left-Turn Phase Sequence on Signalized Arterials. In *Transportation Research Record 1021,* TRB, National Research Council, Washington, D.C., 1983, pp. 53–58.
5. J. D. C. Little and M. D. Kelson. *Optimal Signal Timing for Arterial Signal Systems,* Vol. 1: *Summary Report.* FHWA, U.S. Department of Transportation, Dec. 1980.
6. M. D. Kelson. *Optimal Signal Timing for Arterial Signal Systems,* Vol. 2: *User's Manual.* FHWA, U.S. Department of Transportation, Dec. 1980.
7. M. D. Kelson. *Optimal Signal Timing for Arterial Signal Systems,* Vol. 3: *Programmer Manual.* FHWA, U.S. Department of Transportation, Dec. 1980.
8. C. J. Messer, G. L. Hogg, N. A. Chaudhary, and E. C-P. Chang. *Optimization of Left-Turn Phase Sequence in Signalized Networks Using MAXBAND 86,* Vol. 1: *Summary Report.* FHWA, U.S. Department of Transportation, Jan. 1986.
9. C. J. Messer, G. L. Hogg, N. A. Chaudhary, and E. C-P. Chang. *Optimization of Left-Turn Phase Sequence in Signalized Networks Using MAXBAND 86,* Vol. 2: *User's Manual.* FHWA, U.S. Department of Transportation, Jan. 1986.
10. N. A. Chaudhary and E. C-P. Chang. *Optimization of Left-Turn Phase Sequence in Signalized Networks Using MAXBAND 86,* Vol. 3: *Program Manual.* FHWA, U.S. Department of Transportation, Jan. 1986.
11. K. Paton. An Algorithm for Finding Fundamental Set of Cycles of a Graph. *Communications of the Association for Computing Machinery,* Vol. 12, 1969, pp. 514–518.

12. J. T. Welch, Jr. A Mechanical Analysis of the Cyclic Structure of Undirected Linear Graphs. *Journal of the Association for Computing Machinery,* Vol. 13, April 1966, pp. 205–210.
13. C. C. Gotleib. Algorithms for Finding a Fundamental Set of Cycles for an Undirected Linear Graph. *Communications of the Association for Computing Machinery,* Vol. 10, 1967, pp. 780–783.
14. E. C-P. Chang, C. Messer, and S. L. Cohen. Directional Weighting for Maximal Bandwidth Arterial Signal Optimization Programs. In *Transportation Research Record 1057,* TRB, National Research Council, Washington, D.C., 1986, pp. 10–19.
15. K. G. Baass. Another Look at Bandwidth Maximization.In *Transportation Research Record 905,* TRB, National Research Council, Washington, D.C., 1983, pp. 38–47.
16. K. G. Baass and B. Allard. Description of a Combined Approach for Arterial Signal Coordination Considering Bandwidth and Delays. In *Transportation Research Record 957,* TRB, National Research Council, Washington, D.C., 1984, pp. 32–46.

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Accommodating Transit in TRANSYT

SAM YAGAR

Although the TRANSYT traffic model simulates transit vehicles in mixed traffic operation, it does not adequately consider the effects of bus or streetcar stops on the traveled roadway near signalized intersections. Specifically, it assumes that transit vehicles loading and unloading passengers do not delay other vehicles. This reduces the validity of TRANSYT evaluations for cycles in which buses stop at or very near signalized intersections. The overall TRANSYT predictions and optimizations for an average cycle will be seriously threatened if total bus or streetcar dwell time per hour is significant. Therefore, an alternative type of network formulation, which uses dummy nodes and dummy links with appropriate link costs, is proposed for modeling the effects of transit stops on intersection performance. Although it requires one dummy node and four or six dummy links for each transit stop that delays traffic, it significantly improves TRANSYT's realism for such operations. Parameters for these dummy links have been tested over a wide range, and a set of operational values is recommended. Flow profiles illustrating the need for and effects of the recommended formulation are presented in this paper.

There are a number of models of varying quality for optimizing fixed-time traffic signal splits and offsets on an arterial or a network with signalized intersections. Among these, TRANSYT (*1*) has become the most accepted internationally, on the basis of theoretical evaluations and field tests. TRANSYT attempts to model on-street performance through the use of integrated flow profiles and platoon dispersion. It then calculates initial splits based on equalized saturation and applies a hill-climbing technique in attempting to minimize a weighted combination of delay, stops, and more recently energy consumption. It does this by adjusting offsets and, to a lesser extent, splits at each step of the hill-climbing process.

TRANSYT is quite user-friendly, providing useful echo prints, link- and node-related statistics, and especially graphs of flow profiles for simple visual pictures of how it is dispersing platoons and recombining the flows at intersections.

RECENT MILESTONES IN TRANSYT RELATIVE TO TRANSIT VEHICLES

In 1975, a version of TRANSYT was described (*2*) that allowed the modeling of buses traveling in mixed traffic. This version, called TRANSYT/5 and commonly known as Bus TRANSYT, provided up to five links using each shared stopline. It allowed buses to travel at their own speed, stop for passengers along the way, and be superimposed into a common First-In-First-Out (FIFO) queue at the traffic signal.

In TRANSYT it is assumed that buses travel independently from other traffic between intersections, even though they use the same lanes, and the program allows one to specify differential flow characteristics to represent and simulate any overtaking by or of the buses. Unfortunately, this shared stopline provision only allows buses to queue with other traffic for the traffic signal. It does not allow buses to hold up traffic while loading and unloading passengers in a traveled lane at an intersection. TRANSYT assumes that bus stops are all midblock and clear of intersections, that is, that they do not reduce intersection capacity.

Although this may be the way that buses operate on other continents (which is not fully conceded), bus and streetcar stops in North America tend to occur at intersections in order to facilitate transfers among different transit routes. Although this is not efficient from a traffic-flow standpoint, it is nevertheless a common method of operation and must be so represented in models that purport to represent transit. Even with bus bays, some time is lost as the bus decelerates into the bay from the traveled lane.

In the early 1980s TRANSYT-7F (which stands for Florida) was created by the Transportation Research Centre at the University of Florida (*3*) for the Office of Traffic Operations of FHWA. The data inputs and outputs of TRANSYT 7 were modified to create a North American version. This is now the accepted and most commonly used version in North America, partly because it is free, and it is therefore the version used in this paper. However, TRANSYT-7F did not alter the basic representation of TRANSYT to allow for transit stops at intersections.

TRANSYT/8 (*4*), introduced in 1980, allows for "give-way" situations, but in the context of YIELD or STOP signs rather than of traffic signals. Although this feature might conceivably be altered to represent the effects of buses loading and unloading at traffic signals, there would seem to be major problems of compatibility with variations during the TRANSYT cycle, and so this has not been explored.

TRICKING TRANSYT-7F

An immediate need to test bus and streetcar priority schemes on arterials in Toronto required that appropriate modeling

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formulations be fed into TRANSYT-7F to represent the effects of transit vehicles and other traffic on one another. This was accomplished through the use of dummy nodes and links that had appropriate travel times and capacities. These are described and discussed below.

PROBLEMS WITH TRANSYT'S REPRESENTATION

TRANSYT allows the user to specify dwell times for buses. Therefore, if one specifies 14 sec of dwell time, say, TRANSYT will delay the arrival of the bus at the signal by 14 sec, whether it stops at a midblock location or at the intersection stopline. It will therefore artificially alter the bus's position in the traffic stream and underestimate the delay to cars and other traffic. TRANSYT's procedure in this regard is described below.

TRANSYT estimates the time for a bus to join the queue at the downstream stopline after leaving the previous intersection as the sum of its cruise-related travel time plus dwell time at bus stops. It will therefore assume that cars pass the bus during its dwell time wherever this dwell time occurs, even if it is at the intersection stopline. It then assumes that the bus pulls back into the traffic stream as soon as passengers have been loaded or unloaded and continues to the intersection at its own cruise speed to queue for the signal in mixed lanes of traffic. The basic assumption in TRANSYT is that buses pull off into bays to load or unload, taking 16 sec to travel a distance of 200 ft while accelerating and decelerating for the stop, even if the bus crawls to its loading point in a queue at a traffic signal. It also assumes that buses do not delay traffic in the through lanes during their specified dwell time. This latter assumption is especially critical if TRANSYT is used to model streetcars instead of buses. Streetcars usually travel in the center lanes and therefore stop traffic in all lanes to allow passenger access and egress. Such is the case on Queen Street in Toronto, where the need for the alternative modeling provisions described in this paper originated.

Although effective closure of one or more lanes at midblock locations can also delay traffic, this can be accounted for in the link's cruise speed or travel time, and would in fact be inherent in data collected for this purpose. However, lane blockage during the green phase at an intersection reduces capacity proportionately and keeps other traffic from passing buses and streetcars. TRANSYT does not make adequate provision for these.

MODELING TRANSIT DWELL TIMES

Through the use of dummy nodes and links, TRANSYT can be made to represent the effects of buses or streetcars blocking one or more lanes when they stop to load or unload passengers at an intersection (Figures 1 and 2).

Figure 1 shows the standard TRANSYT representation for a simple signalized intersection (Node 1), which has streetcars and a shared stopline in each direction on the east-west road. The convention used for assigning numbers to links is one or two digits for the downstream node number, followed by one digit to represent possible parallel links, followed by one digit to represent direction of movement. For example, the 1 in Link 104 means flow into Node 1, the 0 means a car-and-truck link, and the 4 means an eastbound flow. Parallel transit links are given numbers in the fifties and are shown as dashed lines (e.g., 152 and 154). TRANSYT allows the user to specify that the parallel Links 104 and 154 share a stopline in order to remerge their flow profiles after they have had their own, independent cruise speeds and platoon dispersions along the link. Because there is no provision for transit vehicles that are loading passengers on Link 154 to delay traffic on one or more lanes of Link 104, the effects of delayed vehicles and reduced capacity are lost. Therefore, alternative modeling procedures are described below for approximating the delays to cars and trucks.

Figure 2 represents an expanded model for Node 1, which allows for streetcars or buses to hold up traffic on all lanes in their direction while they are loading and unloading passengers. The dummy Node 21 and the dummy links leading into and out of Node 21 are used to represent the delaying effects in the eastbound lanes, that is, of Link 154 on Link 104. Similarly, dummy Node 41 and its as-

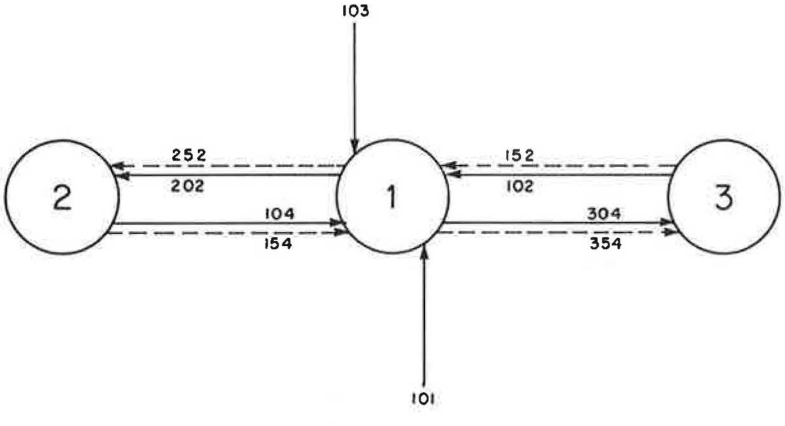

FIGURE 1 Intersection with shared stoplines eastbound and westbound.

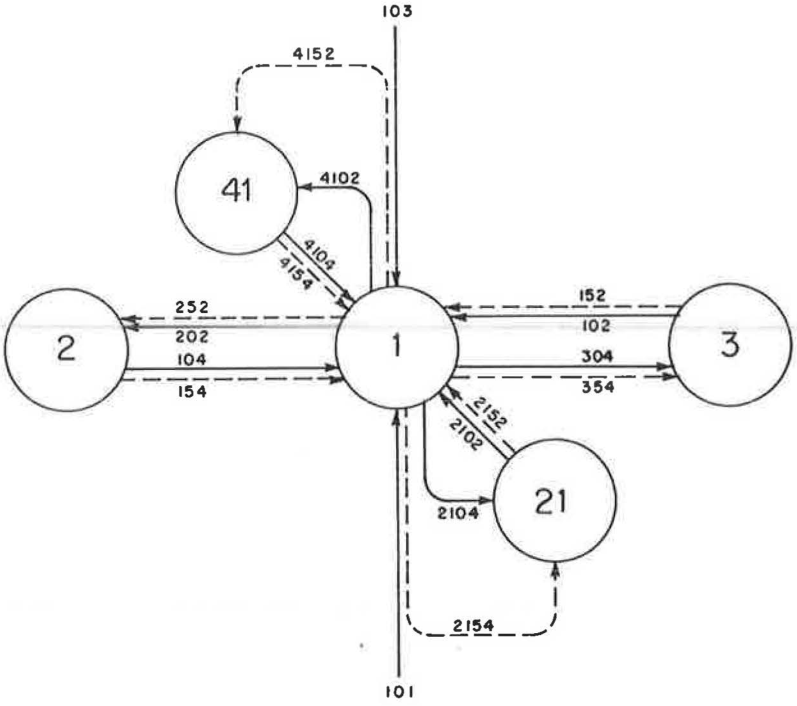

FIGURE 2 Addition of dummy nodes and links to represent full blockage of approach by bus or streetcar loading or unloading passengers.

sociated dummy links are used to stop all westbound traffic while transit is loading and unloading passengers. Note that all dummy links are coded with the number of the dummy node, whether it is their upstream or downstream node, in order to avoid confusion with the real links. The last two digits of dummy links entering a dummy node represent the direction of flow (e.g., 4102 is for westbound cars into dummy Node 41). To draw attention to the fact that dummy links out of a dummy node have the prefix of that originating dummy node, the opposite direction is used for the suffix of the dummy return links (such as 4104) for the westbound flow (i.e., as if Link 4102 had taken vehicles west from Node 1 and Link 4104 was bringing them back east to Node 1). Although somewhat confusing, this convention was adopted after other possibilities had been considered, for lack of a better one.

The key to making this formulation work is in the parameters specified for the dummy nodes. The purpose of the formulation is to require cars and trucks to wait while streetcars load and unload passengers. The procedure is described below for eastbound traffic, and the parameters are listed in Table 1 for both eastbound and westbound links.

Links 104 and 154 queue together at a shared stopline for the eastbound green at Node 1, having traveled from Node 2 at their respective cruise speeds. Cars and trucks from Node 104 then take Links 2104 and 2102 in sequence to Link 304. Because Link 2102 has the same green time as Link 104, the traffic from Link 104 continues through the intersection to Link 304 if Link 104 has a green indication, unless there is a streetcar loading. Link 2104 is red to this car-and-truck traffic when, and only when, the streetcar on Link 2154 is loading or unloading. This is accomplished by giving Link 2154 preemptive priority at Node 21 (through the highest possible weight of 9999), a minimum green time of only 1 or 2 sec, and an amber time that reflects the dwell time while the streetcar is loading or unloading.

To enhance the modeling realism at the first intersection for each direction, the streetcar's flow profile should be compacted into 1 or 2 sec at its original entry into the network by means of a simple dummy intersection providing only 1 or 2 sec of effective green time to the streetcar. This allows a variable number of streetcars (less than or greater than 1 as allowed by TRANSYT) to arrive once per cycle in a small platoon and load or unload for any specified dwell time. If the compacting is not performed that way, before Node 1, for example, Node 21 will accomplish it for downstream nodes, but much of the benefit of this compaction may not be realized at Node 1.

Although it must be assumed that streetcars arrive at the same time in each cycle in order to model fixed-time transit priority, this is believed to be a reasonable requirement in order for fixed-time priority to work at all. It will give some upper bound on the potential benefits from fixed-time priority. If streetcars cannot arrive at about the same point in the cycle for uncongested operation (a requirement of TRANSYT), there is no point in presetting signals to accommodate them. Only tests on Queen Street and other networks can provide some indication of the

TABLE 1 SUMMARY OF PARAMETERS FOR LINKS IN FIGURE 2

Link	Weight	Travel Time	Green Time	Upstream Link
104	1	As Before(2)	As Before	As Before
154	As Req'd(1)	As Before	Shared with 104	As Before
2104	1	0	Cycle Minus Bus Dwell Time	104
2154	9999	0	1 Step (1 or 2 secs)	154
2102	1	0	Same as 104	2104
2152	As Req'd	Dwell Time	Shared with 2102	2154
304	1	As Before	As Before	2102 + Others(3)
354	As Req'd	As Before	Shared with 304	2152 + Others
102	1	As Before	As Before	As Before
152	As Req'd	As Before	Same as 102	As Before
4102	1	0	Cycle Minus Bus Dwell Time	102
4152	9999	0	1 Step	152
4104	1	0	Same as 102	4102
4154	As Req'd	Dwell Time	Shared with 4104	4152
202	1	As Before	As Before	4104 + Others
252	As Req'd	As Before	Shared with 304	4154 + Others

Notes:

(1) As Req'd = The weight accorded to transit vehicles for optimization

(2) As Before = The same values that would have been used if modelled using TRANSYT without the enhancements recommended in this paper

(3) + Others = The flow profile for link 304 now derives its pattern from link 2102 as well as any other links deemed to feed link 304 directly, such as links 101, 103 for turning movements or link 104 for cycles and/or lanes not affected by the transit stops at node 1.

extent to which fixed-time transit priority can improve overall operation.

After the streetcar has passed through Node 21, its travel along Link 2152 takes a time equal to its dwell time. If it gets back to Node 1 while the signal is still green, it can continue to Node 3 on Link 354. Otherwise, it must wait for the next cycle. The entire process at the intersection is realistic, because the streetcar can begin to load or unload into the red period as long as it reaches Node 1 from Link 154 before the end of the green. However, it can only pass through the intersection if the signal is still green when the loading or unloading has finished.

After cars have passed through Node 1 the first time (on Link 104), they simply continue through Node 21 and back to Node 1 via Links 2104 and 2102, instantaneously if there is no streetcar loading. However, if they are following a streetcar, they must wait on Link 2104 until the streetcar has left. The amber time of Link 2154 delays them just enough to allow the streetcar to get back to Node 1 ahead of them. If the signal turns red before the streetcar has finished loading, the vehicles are delayed on Link 2102 until the signal turns green again.

Now, because Links 104 and 2102 could theoretically both be serving queued cars in parallel, the streetcar's effect on intersection capacity could be lost on Link 104. However, the capacity constraint is handled properly on Link 2102. Link 2102 accepts vehicles immediately after Link 104 when there are no streetcars, because Link 2104 would have a red indication and zero travel time. However, when a streetcar stops, cars are queued on Link 2104 and cannot reach the intersection, where the capacity goes begging for the vehicles stuck behind the streetcar. This use of a series of links to model a streetcar stop breaks down the component delays at an intersection as an event-ori-

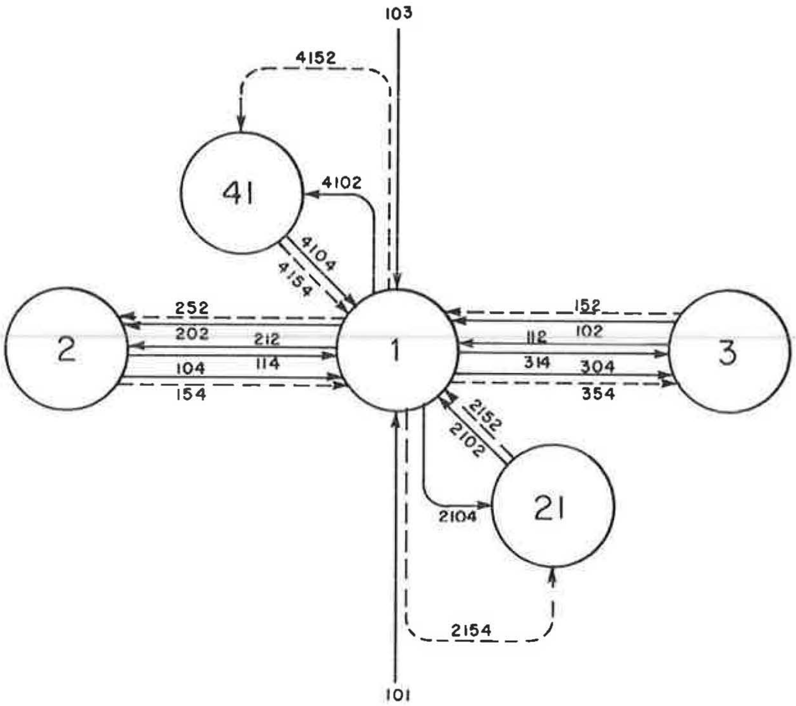

FIGURE 3 Addition of dummy links to allow either full or partial blockage of approach.

ented simulation would do, and actually allows TRANSYT to directly account for carryover to the next cycle, which will be discussed later.

To represent buses that might take up only one lane while allowing traffic on other lanes to pass through, the network of Figure 2 could be expanded by the addition of a through lane for cars not affected by the dummy transit priority considerations. This is represented by Links 114, 314, 112, and 212 in Figure 3. Links 304 and 314 could each have Links 114 and 2102 as partial upstream links to allow for lane changing.

GENERAL AND THEORETICAL DISCUSSION

Varying Saturation Flow

The effective saturation flow for streetcars, in terms of their effect on capacity at a signalized intersection, is very low if they load and unload during the green period; that is, their service headway is very long. For example, if the dwell time and the time taken to accelerate into the intersection are 15 and 3 sec, respectively, the service headway is 18 sec, and the effective saturation flow is 3,600/18 = 200 streetcars per hour of green if this all occurs during the green period. On the other hand, if the streetcar arrives with only 6 sec of green left, it uses up that 6 sec of green time in the loading and unloading process, plus about 3 sec of vehicle service headway time at the beginning of the next green. Now the total service headway is 9 sec, and the effective saturation flow is about 3,600/9 = 400 streetcars per hour of green.

If TRANSYT could accept varying saturation flows during a cycle, or at least different saturation flows for different intervals, one could use an approximation to the curve of effective streetcar saturation flow, as shown in Figure 4, for the foregoing example. Here saturation flow varies monotonically from 200 for streetcar arrivals up to 15 sec before the end of the green to 3,600/3 = 1,200 for streetcar arrivals just at the end of the green.

One might expect that in attempting to minimize the performance index TRANSYT would tend to try to have streetcars either pass through the intersection during a

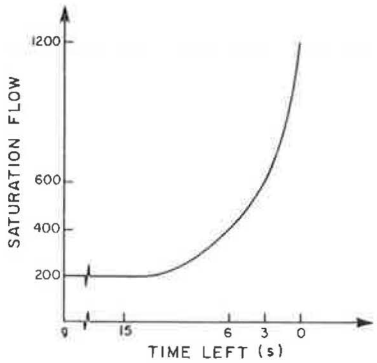

FIGURE 4 Effective streetcar saturation flow versus time left in green phase when streetcar arrives.

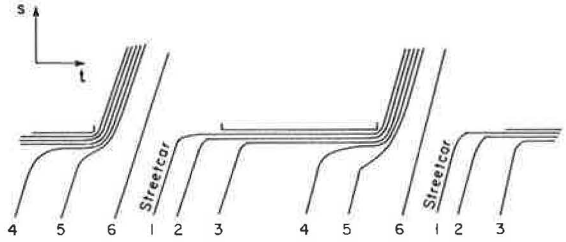

FIGURE 5 Overflow effects of streetcar loading beyond end of green phase.

single green phase or arrive at the very end of one green phase and leave at the beginning of the next one. The latter scenario is the best for streetcars, given that they cannot reach the stopline and load and unload all passengers during a single green phase. It also maximizes the total capacity of the shared approach, as suggested in Figure 4.

Varying Passenger Demand at Streetcar Stops

Some streetcars will not have to stop for passengers at a given stop. If only a small percentage do not have to stop, it can be ignored. If it is large enough that one must represent both stopping and nonstopping streetcars on a link, additional parallel links could be used, similar to those added to Figure 2, creating Figure 3. These streetcars would simply pass through as cars do and would not be disturbed by other streetcars, which would presumably generally not arrive during the same cycle. They could also be given the weights accorded to streetcars. An intricate combination of parallel links could now be employed, as was done with buses to represent partial blocking of the intersection. Again, to simplify the modeling, one might reasonably assume that the probability that a given streetcar would stop at a given stop was independent of whether it had stopped at the previous stop, in determining its relative flows from the modeled parallel upstream streetcar links.

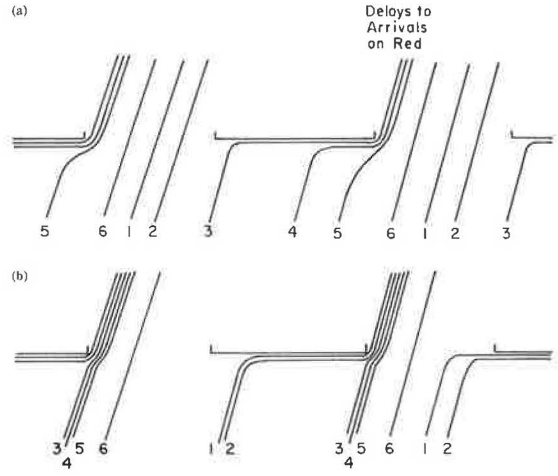

FIGURE 6 Component delays for westbound traffic at Node 1. (a) Delays represented at original shared stopline; (b) queueing of vehicles that arrived during red behind overflow vehicles at return shared stopline at beginning of green.

Platoon Dispersion

One need not specify a bus or streetcar link in order to give vehicles higher weights. The provision for using transit

```
LINK  8102   MAX FLOW   242   VEH/H      LINK  8152  MAXFLOW  1326   VEH/H

00000000000000000000000000000000000            S
00000000000000000000000000000000000            S
00000000000000000000000000000000000            S
00000000000000000000000000000000000            S
00000000000000000000000000000000000            S
00000000000000000000000000000000000            S
00000000000000000000000000000000000            S
00000000000000000000000000000000000            S
00000000000000000000000000000000000            S
00000000000000000000000000000000000            S
00000000000000000000000000000000000            S
00000000000000000000000000000000000            S
00000000000000000000000000000000000            S
00000000000000000000000000000000000            S
00000000000000000000000000000000000            S
00000000000000000000000000000000000            S
00000000000000000000000000000000000            S
00000000000000000000000000000000000            S
00000000000000000000000000000000000            S
00000000000000000000000000000000000            S
00000000000000000000000000000000000            S
00000000000000000000000000000000000            S
00000000000000000000000000000000000            S
00000000000000000000000000000000000      IIIIIIOOIIIIIIIIIIIIIIIIIIIIIIIIIII

---------+---------+---------+-----      ---------+---------+---------+-----
12345678901234567890123456789012345      12345678901234567890123456789012345
```

FIGURE 7 Flow profiles for dummy entry links.

```
LINK   102    MAX FLOW   3380  VEH/H    LINK   152    MAX FLOW   1365  VEH/H

S                                       S
S                                       IS
S                                       IS
S                                       IS
S                                       IS
S                                       IS
S                                       IS
S                                       IS
S                                       IS
S                                       IS
S                                       IS
S                                       IS
S                                 S     IS
S                                 S     IS
S                                 S     IS
S                                 S     IS
S                                 S     IS
SS                                S     IS
SS                                S     IS
SS                                S     IS
SS                                S     IS
SS                                S     IS
000000000000IIIIIIIIIIIIIIIIIIIIII0     IS
000000000000IIIIIIIIIIIIIIIIIIIIII0     I0

---------+---------+---------+-----     ---------+---------+---------+-----
12345678901234567890123456789012345     12345678901234567890123456789012345
```

FIGURE 8 Flow profiles for initial shared stopline.

links is merely a convenience to the user in specifying transit speeds and dwell times. However, if one does use TRANSYT's representation of transit speeds and travel times, one must also accept TRANSYT's estimate that typically about one in eight or so buses will not stop, which is used to increase the variance and reduce travel time on bus links. However, it is easier for the user to understand what is happening to transit flow profiles and to control them if the percentage of nonstopping buses is handled directly through the use of parallel links as shown in Figure 3. Because one also wishes to control the dispersion of the single transit vehicle in a cycle, it is easier to tell TRANSYT that it is just a car, albeit on a very important link, which can be given an appropriate level of priority. In giving this link zero dispersion, one should also reduce its speed to 80 percent of actual cruise speed, because TRANSYT takes it to be the lead vehicle in its platoon, traveling at 125 percent of the specified cruise speed.

Modeling Carryover for Loading into the Red Phase

Dummy links were used to ensure that any cars that were delayed sufficiently behind loading and unloading streetcars to miss the green phase would have to wait for a green after the streetcar had loaded. Figure 5 shows the effect of cars queueing behind a streetcar that is loading and unloading passengers during the last few seconds of green time. These cars must spill over to the next cycle, therefore further delaying the departure during the next green phase of other vehicles that arrive during the red phase. The component delays are represented as follows:

Vehicle 1: streetcar delayed on Link 2152 while loading and then while waiting for green signal;

Vehicle 2: car delayed on Link 2104 until streetcar has loaded; if signal has turned red, Vehicle 2 waits on Link 2102 until signal has turned green again and streetcar has passed through;

Vehicle 3: car waiting on Link 104 for green signal; it passes through Link 2104 and waits on Link 2102 until Vehicles 1 and 2 have been served;

Vehicle 4: car that follows Vehicle 3;

Vehicle 5: car that follows Vehicle 4; and

Vehicle 6: car that is not delayed (has green on Links 104, 2104, and 2102).

Figure 6a and b shows how the component delays are represented at the original shared stopline and the shared stopline for the return dummy links, respectively. In Figure 6a the only delays are to Vehicles 3, 4, and 5, which arrive during the red phase. In Figure 6b, Vehicles 3, 4, and 5 must wait until the overflow Vehicles 1 and 2 leave at the beginning of the green phase. The delays during the streetcar loading are not shown in Figure 6. The proposed disaggregated modeling technique allows TRANSYT to directly account for these delays of queue spillover, as well as represent the transit loading effect on car delays.

For example, Figures 7 to 11 are flow profiles for the westbound flows from Node 3 to Node 2 on the network in Figure 2, which represents the eastern portion of an arterial network in Toronto. Flow profiles are shown separately for the car-and-truck and the streetcar links.

Although Node 1 is the entry node from the east, dummy Node 3 was inserted. It has parallel Links 8102 and 8152

```
LINK  4102    MAX FLOW  3380  VEH/H     LINK  4152    MAX FLOW 1365   VEH/H

I                                       0
I                                       0
I                                       0
I                                       0
I                                       0
I       S                               0
I       S                               0
I       S                               0
I       S                               0
I       S                               0
I       S                               0
I       S                               0
0      SS                         0     0
0      SS                         0     0
0      SS                         0     0
0      SS                         0     0
0      SS                         0     0
0I     SS                         0     0
0I     SS                         0     0
0I     SS                         0     0
0I     SS                         0     0
0I     SS                         0     0
0IIIIII00000                      0     0
0IIIIII00000                      0     0

---------+---------+---------+-----     ---------+---------+---------+-----
12345678901234567890123456789012345     12345678901234567890123456789012345
```

FIGURE 9 Flow profiles for transit priority.

entering. The purpose of inserting dummy Node 3 is merely to give streetcars a spiked flow profile, as in Figure 7. It gives them (Link 8152) 2 sec of green and allows the cars to pass through unimpeded. The streetcar in Figure 7 enters Link 152 from Link 8152 at time step 7 and reaches the downstream end of Link 152 at time step 1 of a later cycle. There it joins the queue of cars on Link 102 and is delayed for one step, as shown in Figure 8, which gives the effect of a westbound shared stopline at Node 1, where Links 102 and 152 must be served by the common east-west green. Note that in this case, Link 8102 was not necessary, because cars could enter the network directly at a constant rate onto Link 102.

Figure 9 shows the effect of a 12-sec (six-step) loading of a streetcar on Link 4152 on the cars of Link 4102, which are held up in steps 2 to 7. Then Link 4154 delays the streetcar for 12 sec, so that it reaches the signal at the appropriate time (i.e., step 8), as shown in Figure 10.

```
LINK  4104    MAX FLOW   2675  VEH/H   LINK  4154   MAX FLOW   1365  VEH/H

        0                                     0
        0                                     0
        0                                     0
        0                                     0
        0                                     0
        0                                     0
        0                                     0
        0                                     0
        0                                     0
0      00                         0           0
0      00                         0           0
0      00                         0           0
0      00                         0           0
0      00                         0           0
0      00                         0           0
0      00                         0           0
0      00                         0           0
0      00                         0           0
0      00                         0           0
0      00                         0           0
0      00                         0           0
0      00                         0           0
0      00000                      0           0
0      00000                      0           0

---------+---------+---------+-----    ---------+---------+---------+-----
12345678901234567890123456789012345    12345678901234567890123456789012345
```

FIGURE 10 Flow profiles for return shared stopline.

```
LINK  202    MAX FLOW   3345  VEH/H     LINK  252   MAX FLOW   1365  VEH/H

              SS                                                0
              SS                                                0
              SS                                                0
              SS                                                0
              SS                                                0
              SS                                                0
              SS                                                0
              SS                                                0
              SS                                                0
              SS                                                0
              SS                                                0
              SS                                                0
              SS                                                0
              SS                                                0
              SSS                                               0
              SSS                                               0
              SSS                                               0
              SSS             I                                 0
              SSS             IIII                              0
I             SSS     0       IIIII                             0
III           SSS     000    IIIIII                             0
IIIIIII       SSS    000000IIIIIIII                             0
IIIIIIIIIIIIIISSS    000000IIIIIIII                             0

---------+---------+---------+-----     ---------+---------+---------+-----
12345678901234567890123456789012345     12345678901234567890123456789012345
```

FIGURE 11 Flow profiles for arrivals to downstream shared stopline.

Because the signal is still green at step 8, the streetcar can go onto Link 252 toward Node 2. Figure 11 shows the effects of platoon dispersion on the arrival of cars at downstream Node 2 via Link 202 and the preserved spike for the streetcar Link 252.

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REFERENCES

1. D.I. Robertson. *TRANSYT: A Traffic Network Study Tool.* Report LR253. U.K. Transport and Road Research Laboratory, Crowthorne, Berkshire, England, 1969.
2. D.I. Robertson and R.A. Vincent. *Bus Priority in a Network of Fixed-Time Signals.* Report LR666. U.K. Transport and Road Research Laboratory, Crowthorne, Berkshire, England, 1975.
3. C.E. Wallace et al. *TRANSYT-7F User's Manual.* Office of Traffic Operations, FHWA, U.S. Department of Transportation, 1983.
4. R.A. Vincent, A.I. Mitchell, and D.I. Robertson. *User Guide to TRANSYT Version 8.* Report LR888. U.K. Transport and Research Laboratory, Crowthorne, Berkshire, England, 1980.

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