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CONTENTS

FOREWORD

By far, the largest portion of America's investment in transportation lies in our vast system of streets and highways. Through the better uses of this ubiquitous street and highway system for bus transit, public transportation service can considerably be increased. The five papers in this RECORD discuss means by which bus transit service can be improved.

Brothers, Benson, and Sheppard report on a planning study conducted for the Los Angeles metropolitan area to determine principal travel corridors for a regional plan of preferential facilities for high-occupancy vehicles. Forecasts of travel diversions to these facilities and traffic impact studies were undertaken. Recommendations are made and cost savings in highway improvements and operating costs are given.

Bakker discusses warrants and criteria for establishing priority treatment for transit. The Edmonton, Canada, experience is described including the public participation before and after an exclusive lane was implemented. The paper also discusses the data needs for development of better standards.

Crain presents a review of the extensive evaluation that is being performed on the 11-mile (18-km) exclusive bus lanes in the median of the San Bernardino Freeway in Los Angeles. Methodology and the findings of the study are discussed including descriptions of commuter profiles, modal split implications, and attitudinal changes of users.

Hoey and Levinson introduce initial suggestions for updating the section on bus capacity in the 1965 Highway Capacity Manual. Presented are background material, analytical approaches, and planning guidelines. Emphasis is placed on planning issues to help transportation planners answer the principal questions relating to the operation of bus systems under various design and service conditions.

DeHsu and Surti discuss a framework of route selection in the bus network design that is based on a proposed functional description and evaluation system. They present a method by which planners can analyze impacts of alternatives in the design of bus networks. A case study using the prepared method is described.

REGIONAL PLAN OF PREFERENTIAL FACILITIES FOR HIGH-OCCUPANCY VEHICLES

Bryant T. Brothers, Daniel E. Benson, and William V. Sheppard,
Wilbur Smith and Associates, Los Angeles

Research and planning were undertaken to identify opportunities and potential demand for the development of preferential facilities for high-occupancy vehicles in Southern California. Preferential facilities include normal or contraflow preferential lanes on existing freeways; exclusive curb, median, contraflow, or reversible lanes on arterials; freeway ramp metering; and associated park-and-ride sites. The treatments were evaluated according to time and cost savings for bus and car-pool users; service deterioration of vehicles with low occupancy; highway agency benefits of capacity improvements and added costs; transit operator patronage, reliability benefits, and increased costs; and community benefits in vehicle mile (vehicle kilometer) and person-minute reductions. Additional objectives were to prepare a comprehensive plan and to supply guidelines for design implementation. A short-range demand forecasting procedure is described, focusing on travel market segmentation and time savings estimates. Results of an impact measurement procedure for a detailed preferential treatment are shown to support recommendations for pilot implementation of a total plan covering 28 service areas, 16 preferential lane treatments, and 485 additional buses.

•SOUTHERN California contains one of the largest and most comprehensive roadway networks ever developed to serve a single metropolitan area. The unprecedented regional accessibility is provided by a major roadway system of >400 miles (644 km) of multilane, limited-access roadways and over 2,000 miles (3220 km) of major six- and eight-lane arterial facilities. Unfortunately, less favorable aspects of the freeway system and of the heavy reliance on the automobile have become apparent in the past decade. Deterioration of air quality is the most obvious; traffic congestion, which once was confined to the approaches of downtown Los Angeles, is now recorded as far as 15 to 25 miles (24 to 40 km) from the central city on all major freeways.

The extensive network of freeways and continued urban expansion have also contributed to the decline in the quantity and quality of public transportation in the region. This decline is a result of the increasing difference between the convenience, comfort, and mobility provided by the automobile and the service levels offered by public transit. This difference becomes especially apparent in the more recent low-density, outlying suburban developments.

Recent federal requirements to improve air quality within Southern California and the experience with gasoline availability have produced an increased public awareness of the need to provide improved transit service. Recognizing the importance of an improved public transportation service, the California State Senate directed the Southern California Rapid Transit District (SCRTD) to develop, by March 1974, a comprehensive plan for the development and operation of preferential facilities for high-occupancy vehicles on the major freeways and arterials in its service area.

The major task of the program was to develop a plan that would enable transit to compete with the automobile in terms of convenience and accessibility and thus encourage transit use. Where feasible, car pools were to be accommodated to encourage an increase in the average occupancy level of commuter automobiles during the peak traffic periods. Major objectives of the study were to

1. Determine the corridors where potential demand for bus and car-pool travel would justify preferential service.
2. Identify opportunities for treatment of existing facilities that would produce significant bus service improvements for current or potential users and that are within the resource capabilities of the agencies that must participate in their implementation.
3. Evaluate the corridors and preferential treatments in relation to the travel impact, costs, and time required to implement the facilities, considering the value that the user, the bus operator, the traffic operations agencies, and the community will gain.
4. Delineate a program for the location and type of preferential service facilities to be implemented.
5. Supply design guidelines and operational procedures for operating buses or car pools on each of the facilities included in the plan.

The types of techniques and criteria for preferential treatments on freeways and arterials were developed from previous preferential applications and research, which therefore served to provide a realistic approach to the improved efficiency of bus transit in Los Angeles.

PREFERENTIAL TECHNIQUES AND CRITERIA

Priority treatments for high-occupancy vehicles have been increasingly implemented throughout the world, and the types of treatment, the number of people they serve, and the design details they use vary widely. The treatments are grouped in three categories: those that relate to freeways, to arterials, and to terminals. Techniques and criteria for application of preferential facilities have been comprehensively documented (1). These were adopted for Los Angeles and have minor adjustments that reflect area characteristics.

Freeway preferential treatments include reserved freeway lanes in both normal and opposite (contraflow) traffic directions and freeway ramp metering on bypass lanes. Arterial treatments include with-flow or contraflow curb and median lanes, which in several instances used overhead, reversible-lane controls. A series of park-and-ride facilities were proposed since such facilities would be necessary in the Los Angeles area to provide collection points for an expanded express bus system.

Both transit buses and car pools would be permitted to use normal-flow freeway preferential lanes and bypass lanes with ramp metering, and only transit buses would be allowed to travel on reserved arterial lanes and contraflow freeway lanes.

TRAVEL CORRIDOR CHARACTERISTICS

Identification of major travel corridors for which preferential treatments are feasible was based on a number of travel and physical criteria. The criteria categories represent a simplified approach to short-range suburban transit planning, based on the identification of high-potential corridors through segmentation of the urban travel matrix. By this means, those corridors were identified in which adequate numbers of similar origin-destination trips are available to provide a diversion to high-occupancy vehicles that is sufficient to justify the implementation of preferential lanes.

Since the preferential facilities are primarily oriented to serving peak-period travel, work trips must form the basis for any diversion analyses to the facilities. The following work-trip-related categories are especially suited for identification of high-potential corridors:

1. Severe peak-hour corridor congestion,
2. Concentration of employment and activity centers,
3. Availability or potential for residential collector facilities,
4. High intensity of work trips in the corridor,

5. Potential for intermediate-range travel growth, and
6. Concentrations of car pools and heavy use of existing transit service.

The criteria were analyzed in the order given above by (a) identifying a bottleneck criterion, high peak-hour corridor congestion, and by (b) identifying several high-volume travel criteria. Each criterion was used to further identify, refine, and segment the highly dispersed Los Angeles metropolitan travel market into sensible corridors.

Heavily traveled corridors that experience high congestion levels were identified. Each corridor was investigated to locate high-employment centers that could be served, and areas with lesser or more dispersed employment were eliminated from further investigation. Outlying residential service areas were selected that exhibited a satisfactory potential for sufficient diversion to transit. Those residential areas that were located too close to the destination, <5 to 8 miles (<8 to 13 km) (3), to permit an adequate time savings or that had too little population to demand relatively frequent and attractive service were assigned lower potential ratings.

For those origin-destination pairs remaining in a corridor, those with low zone-to-zone peak-hour travel were eliminated. A minimum diversion level sufficient to require two peak-hour bus runs between the outlying feeder run or park-and-ride area and the activity center was used to screen the origin-destination service area pairs. The potential for increased future travel between each of the origin-destination pairs was examined by using residential, employment, and travel projections based on regional growth forecasts. It was considered especially desirable to establish service in corridors for which the SCRTD was proposing a mass rapid transit service. Final emphasis was placed on the corridors that currently are heavily used by transit and car pools. SCRTD patronage studies and consultant field surveys of car occupancies provided the necessary input to establish relative corridor priorities.

Major peak-period travel corridors identified through this procedure were the Ventura-Hollywood, San Bernardino, Santa Ana, Santa Monica, San Diego, Long Beach, and Pasadena Freeways to downtown Los Angeles.

EVALUATION OF ALTERNATIVE PREFERENTIAL TREATMENTS

Specific major roadway facilities were selected for detailed investigation within each of the eight travel corridors that were identified as having the potential for preferential treatment of high-occupancy vehicles. Review of as-built construction plans and field reconnaissance of each roadway were used to establish which treatment types were physically possible. Data for traffic volume and speed were obtained to determine potential speed differentials afforded by particular treatments. After a preliminary review of the data for each roadway, those alternative treatment types appearing feasible from an operational standpoint were identified for detailed evaluation. Twenty-six major treatments on 16 different roadways were considered.

The high-occupancy vehicles assigned to use each preferential treatment consist of existing scheduled transit buses, existing car pools, and projected transit vehicles serving park-and-ride facilities. The two existing elements were determined from traffic and transit inventories, and 28 park-and-ride facilities were developed as collector areas for suburbia. Park-and-ride buses were determined by estimating diversion to transit in each service area and then calculating the number of buses necessary to serve the estimated demand. These vehicles were then assigned to the fastest route to the appropriate activity center destination.

Impacts

Evaluation of the preferential treatments required that a set of impact parameters be identified to facilitate the comparison of alternate treatments with the status quo.

First, the potential impacts of preferential treatment for high-occupancy vehicles were categorized by the groups or agencies that would be most directly affected by such treatments (Table 1). Individual impacts were then defined as either benefits or disbenefits received by the group or agency. Finally, one or more parameters that provide a quantitative measure of each impact were determined.

Most of these impacts can be measured in terms of the following variables:

1. Travel time savings to preferential vehicles,
2. Projected increases in peak-hour transit patronage,
3. Peak-hour person-trip movements,
4. Peak-hour vehicle miles (vehicle kilometers) of travel,
5. Peak-hour person minutes of travel, and
6. Estimated capital and operating costs.

These measures, as well as the operational safety of the facility, were evaluated for each facility.

Travel Time Savings to Preferential Vehicles

An estimate of the anticipated travel time savings experienced by high-occupancy vehicles was developed for each of the alternate preferential treatment plans on each facility. Present automobile and transit travel times were determined from data supplied by the California Department of Transportation and the SCRTD. These data were supplemented with actual peak-period travel time runs.

Preferential vehicle travel times (for buses serving the park-and-ride system) were determined by estimating the time required to complete each segment of a theoretical trip from the front door to the park-and-ride lot, to the freeway, and to the activity center destination. Preferential travel time was estimated from each park-and-ride facility to the activity centers served by it.

The travel time for each of the 28 park-and-ride service areas to the major activity centers, based on the various preferential treatments, was compared with existing times. In several instances, the preferential travel time savings is negative. This occurs when the time savings resulting from preferential treatment is not sufficient to offset the additional time required to travel to the park-and-ride facility and wait for a bus.

Projected Peak-Hour Patronage

Magnitude of existing home-to-work travel desires between each park-and-ride service area and the major activity centers was determined through an analysis of the 1967 home interview survey data of the Los Angeles Regional Transportation Study (LARTS), which was supplemented with 1970 census home-to-work data.

A marginal utility model, for Los Angeles (3), was used to estimate the patronage that would be expected to use each park-and-ride facility if preferential treatment for buses was provided. This model translates transit travel time and cost savings between the service area and the activity center into a percentage of the diversion of the work-trip travel to transit.

Travel times developed in the preceding step and the home-to-work data were used to estimate peak-period patronage from each park-and-ride service area to the major activity centers. In Los Angeles, approximately 55 to 65 percent of all peak-period morning work trips occur in the peak hour. Thus, peak-hour patronage was estimated as 60 percent of total peak-period patronage. Peak-hour bus assignments to each park-and-ride site were designed to accommodate the estimated peak-hour patronage with an 80 percent load factor. Service between a specific park-and-ride facility and an activity center was not considered if less than three buses were required to serve the estimated peak-hour demand.

Peak-Hour Person-Trip Movements

Peak-hour person-trip movements on each facility were analyzed with and without preferential treatment. Peak-hour traffic count and automobile occupancy data were compiled to determine the existing peak-hour person-trip movements via bus, car pool, and low-occupancy vehicles for each facility. The same analysis was again performed for each facility with the proposed alternate preferential treatment plans by taking into account the projected peak-hour bus volumes assigned to that facility and the associated diversion of existing automobile travelers to the park-and-ride, preferential lane system.

The provision of preferential treatment significantly increased the estimate of peak-hour person-trip use of the lane designated for buses and car pools relative to the peak-hour person-trip volumes in the adjacent nonpreferential lanes.

Peak-Hour Vehicle Miles (Vehicle Kilometers) and Person Minutes of Travel

Peak-hour vehicle miles (vehicle kilometers) and person minutes of travel were also determined for buses, car pools, and nonpreferential vehicles for each of the alternate preferential treatment plans. The implementation of preferential treatment reduces total vehicle miles (vehicle kilometers) of travel and the person minutes of travel by persons using the preferential lanes. At the same time, the person minutes of travel for nonpreferential lane users may increase because of increased traffic densities, and, for several alternatives, this increase offsets the person-minute savings to preferential lane users.

Operations and Safety

Operational considerations were analyzed with regard to safety for both preferential and nonpreferential traffic. When priority treatments are implemented, the character of existing traffic will be altered by varying degrees. This alteration in traffic character is precipitated by two somewhat opposing factors—reduced total numbers of vehicles through person-trip diversion to transit and car pools and increased lane densities for nonpreferential traffic. The extent to which this alteration is beneficial or detrimental to operating conditions is examined for each priority treatment, and the qualitative assessment of the safety impact is expressed as one of five levels ranging from a major increase to a major decrease in accident potential.

The analysis of nonpreferential traffic was embodied in the ramifications of increased or decreased vehicular volumes, i.e., change in traffic flow, increase or reduction in lane changing, and change in ramp volumes. The analysis of preferential traffic confined itself to considerations of speed differentials between preferential and nonpreferential traffic, weaving at the preferential lanes' initial and terminal points, and incidents in the preferential lane.

Cost

Capital and operating costs were estimated for each of the alternative treatment plans. For normal items, cost estimates were determined primarily by using per-mile (per-kilometer) unit costs for different cost categories. For unusual construction problems, more detailed cost estimates were made.

Selection of Alternative Treatments

For each alternative treatment on each facility, the six impact evaluation parameters were determined as previously described. A summary of the parameters for each of the major preferential treatments is given in Table 2. This summary provides a planning basis for selecting the alternative preferential treatment plan that is best suited to each facility. The comparisons also provide a means of determining those facilities that provide the greatest benefits with the lowest costs and least disruption to traffic. In this manner, priorities are also determined for the preferential lane treatments.

A reduction in the total vehicle miles (vehicle kilometers) of travel can be directly associated with a reduction in fuel consumption and lower levels of total vehicle exhaust emissions. Reductions in the total person minutes and total vehicle miles (vehicle kilometers) of travel and no decrease in the total person trips accommodated by the travel corridor indicate that the person-carrying capacity of the corridor has been used more effectively. Thus, both of these impact criteria offer a measure of the relative efficiency of the transportation system before and after the implementation of a preferential treatment.

When preferential treatment is implemented, the number of persons and vehicles using the preferential lanes should increase from those using the lane under existing mixed traffic conditions. An increase in person-trip use of the preferential lane for a facility may also result in increased travel speeds for nonpreferential traffic.

Estimated capital and operating costs for each facility provide a cost measure to be weighed against the potential benefits offered by each preferential treatment plan.

Regional Ramp Metering

Ramp metering on a bus- and car-pool bypass can be effective for providing preferential treatment to high-occupancy vehicles. A regionwide application of preferential ramp control may, however, have several inherent disadvantages.

Preferential ramp control will affect specific groups of motorists more than others. Motorists living close to a freeway with sustained traffic volumes will be metered off the freeway or experience substantial delays in entering the freeway. Motorists living adjacent to a freeway in an outlying lower demand area will have significantly greater freeway access. Generally, long-distance automobile trips are encouraged because when the drivers are on the freeway they will experience little or no delay. Short-distance trips will be rerouted to the arterial street system or will experience the necessary delay on the freeway ramp approach.

Preferential Lane Versus Ramp Metering

The preferential lane concept is designed to divert long, low-occupancy vehicle trips to either transit or car pools, and the ramp-metering concept provides no substantial impetus to discourage low-occupancy automobiles and would encourage increased low-density urban expansion. No significant incentive is provided to divert long-distance trips to high-occupancy vehicles. Long-distance trips would be most easily converted to transit and car pools because the park-and-ride access and wait time or the car-pool circulation and pickup time is a small portion of the total trip travel time. Ramp metering on bypass lanes with high-occupancy vehicles would provide a disincentive to short-distance, low-occupancy trips, although these trips are least likely to divert to high-occupancy vehicles and are more likely to use arterial street alternative routes.

Considering the above, the potential diversion to high-occupancy vehicles induced by a comprehensive system of preferential ramp metering would be significantly less than that offered by a park-and-ride, preferential lane system.

RECOMMENDED PLAN

The preferential treatment plan developed for high-occupancy vehicles was intended to

Table 1. Preferential treatment impacts.

Item	Benefits	Disbenefits	Quantitative Measure of Impact
Preferential bus and carpool users	Travel time savings Travel cost savings Improved reliability in arrival time Relaxation	Schedule conformance Loss of personal vehicle for use during midday to those diverted to buses	Travel time savings Duration and frequency of proposed transit service
Nonusers of low-occupancy vehicle	Possible improvements in traffic conditions Possibility of a viable alternative to low-occupancy vehicle use	Possible increase in travel delays, travel costs, and accident potential Reduced reliability of arrival time	Level of service Accident rates
Freeway and highway operations	Possible increases in roadway capacity through addition of new lanes and in person-trip throughput of the facility Possible improvements on existing travel lanes	Possible increase in nonpreferential congestion Additional equipment and personnel to maintain and operate preferential facilities Increased enforcement costs	Increased occupancy Level of service Operation and enforcement costs
Transit operators	Increased patronage Marketing advantage for transit in travel time savings and visibility	Higher operative and capital costs Less use due to peaking and deadheading	Patronage Capital and operating costs Required frequency and duration of proposed transit service
Community environmental energy impact	Reduced vehicle miles (vehicle kilometers) of travel per person	Start-up vehicle exhaust emissions[a] generated in traveling to a park-and-ride site	Vehicle miles (vehicle kilometers) of travel Person minutes of travel Fuel consumption

Note: 1 vehicle mile = 1.6 vehicle km.

[a] These are a high proportion of total-trip exhaust emissions.

Table 2. Summary of preferential treatment evaluation.

		Peak-Hour Travel			Estimated Annual Treatment Costs ($)		
Region and Roadway	Treatment	Vehicle Mile Reduction	Person Minute Reduction	Preferential Lane Use (persons/hour)	Capital	Operating	Accident Potential
San Fernando Valley							
San Diego Freeway	Normal flow	15,710	14,800	800	340,000	68,000	Minor increase
	Normal flow in shoulder lane	15,710	42,690	—[a]	3,010,000	520,000	No change
Hollywood Freeway	Normal flow	26,240	24,820	2,490	460,000	81,000	Minor increase
	Contraflow	26,240	26,880	—[a]	1,880,000	1,040,000	Minor increase
Ventura Freeway	Normal flow	3,990	-4,070	-80	290,000	86,000	Major increase
La Brea Avenue	Reversible lanes	—[a]	1,800[b]	590	325,000	57,000	Minor decrease
San Gabriel Valley							
San Bernardino Freeway	Normal flow	13,630	24,830	1,570	992,200	113,000	Minor increase
Pasadena Freeway	Contraflow	4,600	20,790	—[a]	590,000	710,000	Minor increase
North Broadway	Reversible lanes	—[a]	2,500[b]	850	165,000	25,000	Minor increase
West Los Angeles-Santa Monica							
Santa Monica Freeway	Normal flow	11,580	-7,720	-860	330,000	92,000	Major increase
	Normal flow in shoulder lane	11,580	25,590	—[a]	2,045,000	376,000	Minor decrease
Wilshire Boulevard	Contraflow	—[a]	30,000[b]	1,280	1,192,000	144,000	No change
Pico Boulevard	Reversible lanes	—[a]	3,200[b]	1,020	620,000	75,000	Minor decrease
South Bay							
Long Beach Freeway	Normal flow	37,400	25,350	1,900	409,000	100,000	Minor increase
	Normal flow in shoulder lane	37,400	80,440	—[a]	3,204,000	562,000	Minor decrease
Harbor Freeway	Normal flow	15,360	12,380	340	400,000	99,000	Major increase
	Contraflow	15,360	12,160	—[a]	469,000	2,092,000	Major increase
San Diego Freeway	Normal flow	40,800	13,440	340	988,000	172,000	No change
	Normal flow in shoulder lane	40,800	73,780	—[a]	7,721,000	1,285,000	Minor decrease
Flower Street	Reversible lanes	—[a]	4,600	2,470	390,000	56,000	Minor decrease
Orange County							
Santa Ana Freeway	Normal flow	35,440	85,330	340	949,000	157,000	Major increase
Artesia Freeway	Normal flow	20,490	6,120	120	625,000	115,000	Major increase
	Normal flow in shoulder lane	20,490	11,990	—[a]	1,350,000	310,000	Minor decrease
San Diego Freeway	Normal flow	16,700	17,670	50	546,000	109,000	No change
	Normal flow in shoulder lane	16,700	52,520	—[a]	4,267,000	818,000	Minor decrease
Whittier Boulevard	Reversible lanes	—[a]	5,600[b]	165	435,000	65,000	Minor increase

Note: 1 vehicle mile = 1.6 vehicle km.

[a] Not applicable.

[b] For transit passengers only.

promote increased car-pool and transit use to assist the area in attaining regional goals involving air quality, energy consumption, and maximum use of existing travel facilities. The plan is based on the comprehensive analysis of the alternative treatment plans in each corridor and includes a careful assessment of resulting transit service and traffic impact.

The plan includes 28 park-and-ride facilities, preferential lane treatments for 8 freeways and 6 arterials, and a downtown distribution plan. These facilities would vastly improve current transit service levels and would provide increased stimulus for use of buses and car pools.

Park-and-Ride Locations

Extensive areas of single-family housing units and dispersed residential areas such as those in Los Angeles are usually characterized by ineffectual transit service and low ridership. To offset these features, a series of 28 park-and-ride collection points are proposed for the area (Figure 1). These facilities were located as far away from the activity center destinations as feasible to provide preferential transit service for as great a part of the travel route as practical. Required sizes of the park-and-ride facilities range from 300 to 1,300 parking spaces to accommodate the estimated demands.

Preferential Facilities Plan

Preferential lane treatments for high-occupancy vehicles were recommended for all of the major regional sections of the SCRTD service area. The extent and type of recommended treatment for each of the 8 freeways and 6 arterials are shown in Figure 2. These treatments include the following:

1. Hollywood Freeway—a 5-mile (8-km) normal-flow lane;
2. San Diego Freeway—a 31-mile (50-km) preferential lane on the shoulders;
3. San Bernardino Freeway—a 5-mile (8-km) normal-flow lane;
4. Long Beach Freeway—an 11-mile (18-km) normal-flow lane on the improved shoulder;
5. Artesia Freeway—an 8-mile (13-km) normal-flow lane on the improved shoulder;
6. Santa Monica Freeway—an 8-mile (13-km) normal-flow lane on the improved shoulder;
7. Harbor Freeway—8 miles (13 km) of normal flow in the existing lane;
8. Ventura Freeway—3 miles (4.8 km) of normal flow in the existing lane;
9. Wilshire Boulevard—4 miles (6.4 km) of contraflow median lanes;
10. La Brea Avenue—a 2-mile (3.2-km) bus-priority, reversible lane;
11. Flower Street—a 2-mile (3.2-km) bus-priority, reversible lane;
12. Whittier Boulevard—a 2.5-mile (4-km) bus-priority, reversible lane;
13. North Broadway—a 1-mile (1.6-km) bus-priority, reversible lane; and
14. Pico Boulevard—a 2.5-mile (4-km) bus-priority, reversible lane.

Projected evening peak-hour use of the facilities is shown in Figure 3. Maximum use is projected for the Hollywood Freeway south of the Ventura Freeway. Peak-hour lane use on that facility totals 102 buses and 400 car pools for 5,400 person trips.

Weekday use of all 14 preferential lane treatments would total 2,700 bus trips and 7,000 car-pool trips. These vehicles would accommodate a total of 135,000 daily person trips. Annual travel distance and time savings associated with the preferential lanes are estimated at 180,000,000 vehicle miles (289 700 000 vehicle km) and 6,100,000 person hours. The projected preferential lane use approximates 2 percent of total travel during peak periods.

Figure 1. Proposed park-and-ride locations.

Figure 2. Preferential lane treatment.

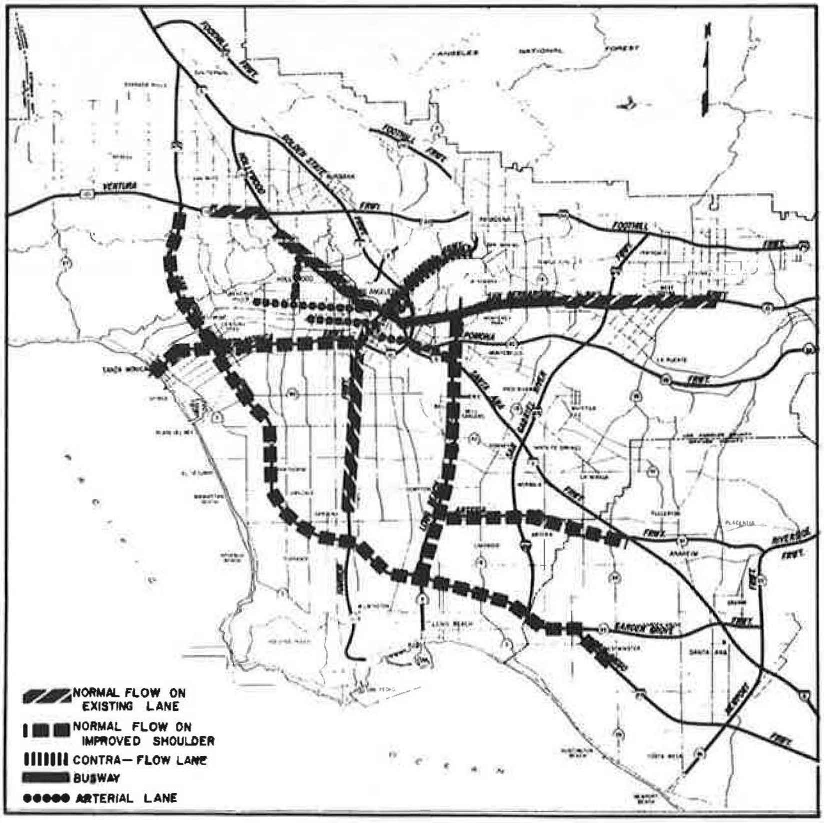
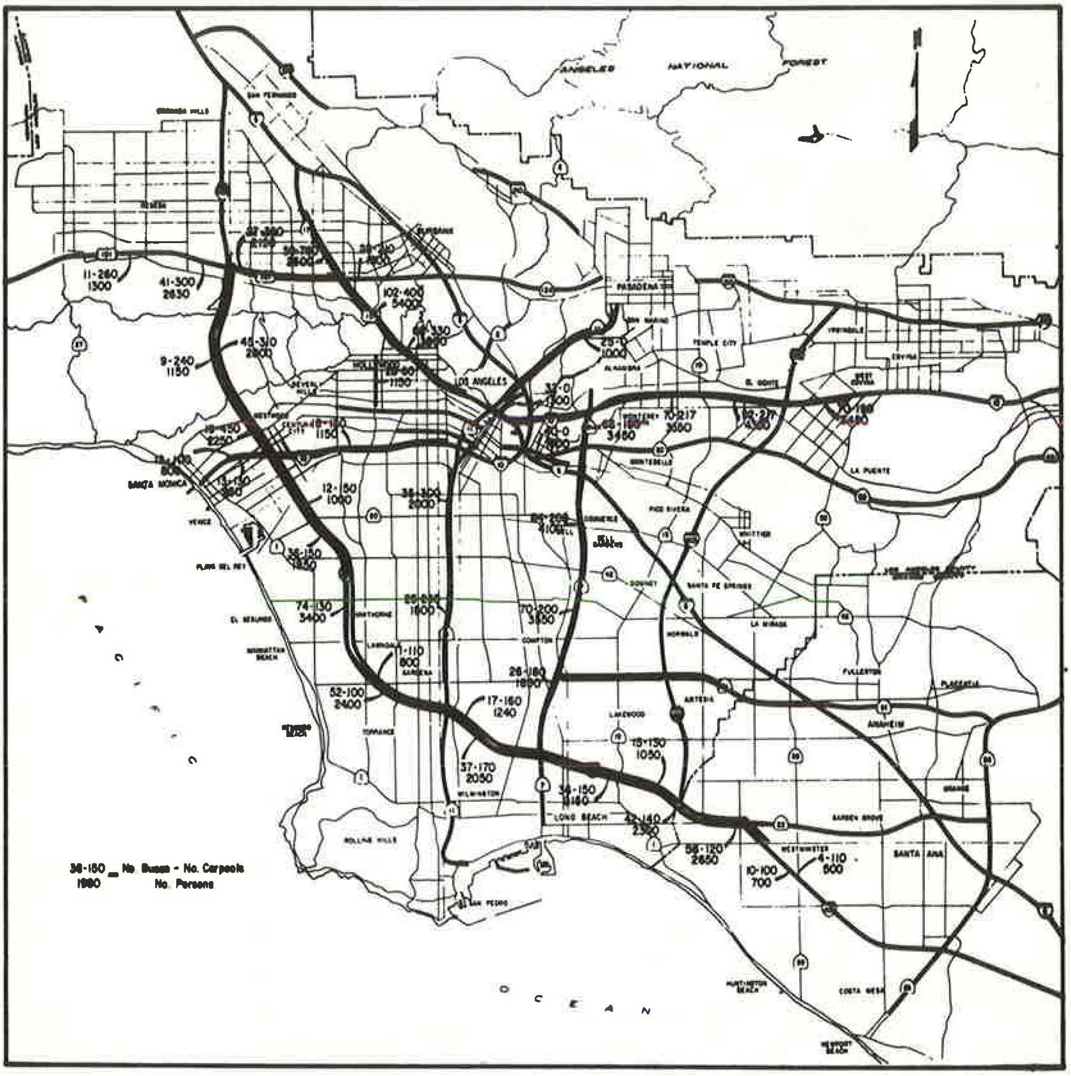


Figure 3. Preferential lane use, p.m. peak hour.



Distribution in Downtown Los Angeles

Routing and operation of transit buses on the approach to and circulation within the Los Angeles downtown area, the largest single activity center, are essential components in the overall regional program. This is especially true because of the large number of additional buses (150 to 200) that would enter and exit downtown Los Angeles during the morning and afternoon peak traffic hours.

In 1973, a bus-priority lane (4) was adopted for the downtown distribution routes of express buses from the Los Angeles-El Monte Busway. The plan includes contraflow bus lanes on two one-way couples, one on the east side to serve the older commercial areas and one on the west side to improve service to the fast-growing financial district. Los Angeles presently has a contraflow southbound bus lane on 10 blocks of Spring Street on the east side of the downtown area.

Distribution and loading of express buses on the east side of downtown would use Spring Street to take advantage of the contraflow bus lane. On the west side, Flower Street would be used as the distribution route through the financial district since the proposed bus-priority, reversible-lane system could be used between the freeway loop and the south limit of the intensely developed core area.

Priorities

A determination of priority groups is necessary to implement a preferential facility treatment program as extensive as that developed in this study. Such scheduling groups were outlined to allow certain treatment types that have not been previously used in the Los Angeles area to be tested under actual traffic conditions before further sections were implemented. The experience and results gained from the operation of the initial project of normal-flow bus and car-pool freeway lanes, median contraflow bus lanes, and bus-priority, reversible-lane systems will assist in the implementation and operation of subsequent projects using similar treatment types.

Program Cost

Capital costs to implement the proposed preferential lane treatments are estimated to be $27,490,000. Annual costs of $5,392,000 will be necessary to maintain and operate these treatments. Acquisition and improvements of the 28 park-and-ride facilities will require $8,480,000, and annual operating expenses are estimated to be $1,424,000.

Total annual capital and operating costs for the proposed additional transit services are estimated to be $18,693,000. This estimate includes $1,193,000 in annual capital cost expenditures for acquisition of the proposed 485 new buses and their support facilities and $17,440,000 for annual operating costs.

PLAN IMPLEMENTATION

Implementation of a portion of the proposed program for preferential facilities has been initiated by the California DOT and SCRTD. At present, eight park-and-ride facilities have been opened for service in addition to the El Monte facility, which had been constructed prior to the study. In February 1975, a tenth facility will be served by SCRTD.

The California DOT is preparing to implement normal-flow preferential lanes on the Santa Monica Freeway and contraflow lanes on the Hollywood Freeway. The two initial facilities, in addition to the Los Angeles-El Monte Busway, will provide the Los Angeles region with observation and testing of three types of preferential lane facilities. After satisfactory operations have taken place on these, similar facilities will be initiated in other major travel corridors.

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PUBLIC TRANSIT RIGHT-OF-WAY

J. J. Bakker, Department of Civil Engineering, University of Alberta

This paper deals basically with when, where, and how priority treatment for transit should be provided. It is suggested that total people delay be used as the criterion for developing standards. Several examples are cited of exclusive transit rights-of-way, particularly in Europe and western Canada. In addition, some examples are given of exclusive signals used in Europe and in Edmonton, Alberta. The Edmonton experience is described including public participation before and after an exclusive lane was implemented. The paper concludes that there is a need in transportation agencies for a more uniform basis of data collection before and after implementation so that better standards can be developed.

•HISTORICALLY the streetcar had the right-of-way over other forms of transportation, but, as there has been a changeover to buses, transit no longer has right-of-way privileges that are different from other vehicular traffic.

As the level of service becomes lower because of increased traffic density, the operating speed of transit will be reduced. This reduction in speed will mean that, to maintain the same frequency of service, more buses will be required. In other words, the productivity of transit is reduced at a time when costs are increasing greatly and the potential demand is the highest.

To overcome this problem, the solution of providing exclusive rights-of-way to transit or of giving priority treatment to transit should be considered. The problem is basically when, where, and how this priority treatment should be provided.

DELAY AS A CRITERION

To reduce delay is the basic reason for implementing exclusive rights-of-way for transit; therefore, one must determine the total people delay and see whether this delay can be reduced by providing exclusive lanes.

The traffic engineer generally uses vehicle delay as a tool, for example, in setting traffic lights. A more objective measure would be the criterion of people delay, which uses the occupancy of the vehicles as a weighting factor.

Measuring delay at an intersection has been studied as a result of improving signal timing at an intersection or in a network. There are two basic cases:

1. Where the arrival pattern of vehicles in the queue is not known. In this case an estimate of vehicle delay can be made by using the simplified expression (3)

$$d = \left[\frac{g}{10} \frac{c(1 - \lambda)^2}{z(1 - \lambda\chi)} + \frac{\chi^2}{2q(1 - \chi)} \right]$$

where

d = delay in seconds,
λ = green to cycle time ratio = g/c,
g = green time in seconds,

c = cycle time in seconds,
q = actual flow in passenger cars per second,
s = saturation flow in passenger cars per second, and
χ = degree of saturation = $q/\lambda s$.

Field tests in Edmonton show that this expression gives results within 5 percent of actual delay.

2. Where the arrival pattern is known, as in the case of a simulation model of a signalized network or by actual counts. Departures are computed by assuming that the vehicles will leave the queue at the saturation flow during the green time.

Delays based on the arrivals and departures in the queue are shown in Figure 1 (4). The area below the arrival curve and above the departure curve will give the total delay.

To get the people delay, an average occupancy per vehicle has to be determined, preferably with occupancy counts. People delay is, therefore, vehicle delay weighted by the average occupancy per vehicle.

For an exclusive transit lane, the transit vehicles and their occupancy have to be excluded from the lanes available to other vehicles. The transit vehicle delay weighted by its occupancy can then be added to obtain the total people delay.

If the people delay occurring now is compared with the delay that would occur if there were traffic separation, an assessment can be made about whether the scheme is desirable or not. This type of evaluation is often better than the rules that specify number of buses per hour, number of lanes available, and total traffic volume. There is no reason why, on roads that are overdesigned or wastefully used, exclusive transit lanes should not be implemented. The big problem, however, is to obtain hard data and reliable methods of predicting the delay of mixed or separated traffic. In fact, the greatest benefit of an exclusive transit lane is the predictability of the speed of transit operation; this means that the reliability of the schedule can be assessed. This reliability of service is often more important on routes with an infrequent service than on those that have a frequent service.

WHERE TO USE TRANSIT LANES

In Europe there are now many examples of exclusive lanes for transit. Generally, these lanes have been established where the traffic congestion was severe and the delay became unbearable.

The Hague has no rapid transit system and relies on both streetcars and buses for its transit service. The city has a business center, two railway stations, a government center, and a seaside resort and has progressively extended exclusive transit lanes, usually in the median of the road. These transit lanes are used by streetcars, city transit buses, and interurban buses. The plan is to provide grade separation in the downtown core for the streetcars; hence the term premetro. New rail transit lines are also built to the outlying areas. This city pioneered in Holland an integrated route and fare system with the railways and interurban bus system.

Rotterdam has a rapid transit line linking both sides of the harbor. The surface system, as in the Hague, provides the remainder of the network. One line going north has an exclusive grade separation over an arterial road, a canal, a railway line, a freeway, and another road.

Delft not only has reserved transit lanes but also uses exclusive signal control. Loop detectors are buried below the exclusive lane and give a 4-sec transit phase whenever it can be fitted in the signal timing program. If there is a near-side stop, a double stop line is used because the loop detector is between the stop lines. The same principle is often applied at congested intersections where an exclusive approach lane is provided for transit.

Paris now provides many miles of curb lane that are reserved for buses or taxis. Usually these lanes replaced curb parking.

Edmonton, Calgary, and Vancouver in western Canada have implemented exclusive bus lanes; other bus lanes are in operation in Toronto. There are many bus lanes in the United States and in other countries in Europe.

Other schemes give priority to transit, such as permitting left turns by buses in locations where such turns are generally prohibited.

In Edmonton, bus crossing signals have been tried in a few locations since June 24, 1974. These signals are installed at a STOP approach and are actuated by the bus driver using a small transmitter. The signals are similar to a pedestrian crossing signal and in fact work in conjunction with a pedestrian crossing. The green time allowed for the bus is 4 sec, and the walk time for pedestrians is 10 sec; a clearance time of 6 sec is added to these times. Currently these signals are still experimental. Installation of traffic signals at these intersections may be justified based on traffic warrants but would encourage traffic detouring through residential areas. The locations are generally at a collector-arterial road intersection.

When first tried, the signal indication of the main arterial road was flashing yellow, which would change to steady yellow and then to red. However, flashing yellow means caution and a speed limit of 20 mph (32 km/h). The flashing yellow was changed to a normal green light; therefore, on the main road the signal looks no different than a normal traffic light. The side street, however, has a stop sign and pedestrian signals and the special transit T-signal.

Numerous other examples are given elsewhere (1) for many locations in the world.

Invariably all these schemes were implemented so that buses could bypass traffic congestion. The methods used varied: exclusive curb lanes, median lanes, contraflow lanes on freeways, contraflow lanes on one-way streets, or exclusive roads for buses (e.g., in Runcorn, England).

The suggested warrants of the Institute of Traffic Engineers for bus lanes are too restrictive:

1. A curb lane is practical under normal circumstances only during peak traffic periods when curb parking and stopping regulations can be implemented;
2. A minimum of 60 transit vehicles/hour should use the transit lane;
3. The width of the roadway must be sufficient for at least two lanes of travel in addition to the transit lane in the direction of the transit lane; and
4. The number of transit patrons should equal or exceed 1.5 times the drivers plus passengers carried by other vehicles in the peak hour.

Other criteria that should be considered, however, are as follows:

1. What is the present lane use? In Edmonton on 109th Street, one traffic lane was used by a few left turners. An exclusive bus lane along the curb could be created by banning the left turns in the peak hour and by moving the two other traffic lanes over. The seven-block length is peculiar in that the road is an approach to two river crossings, both of limited capacity. The buses now bypass the traffic lineup (Figure 2).
2. What is the total people delay now, and what will it be if traffic is segregated into bus and car lanes?
3. What is the total vehicle delay now and after implementation of a bus lane, and can this delay be reduced with a revised signal timing plan?

Implementation of exclusive bus lanes does not necessarily produce dramatic savings in time. However, the reliability of bus travel time will be greatly improved because schedules will become reliable, which, in turn, will mean shorter waiting times at the bus stops.

Figure 1. Delay based on arrivals and departures in the queue.

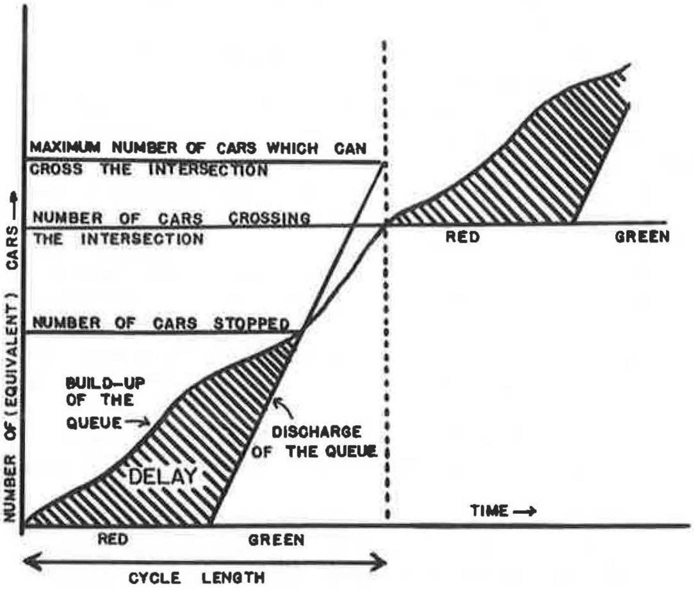


Figure 2. Exclusive bus lane project on 109th Street.

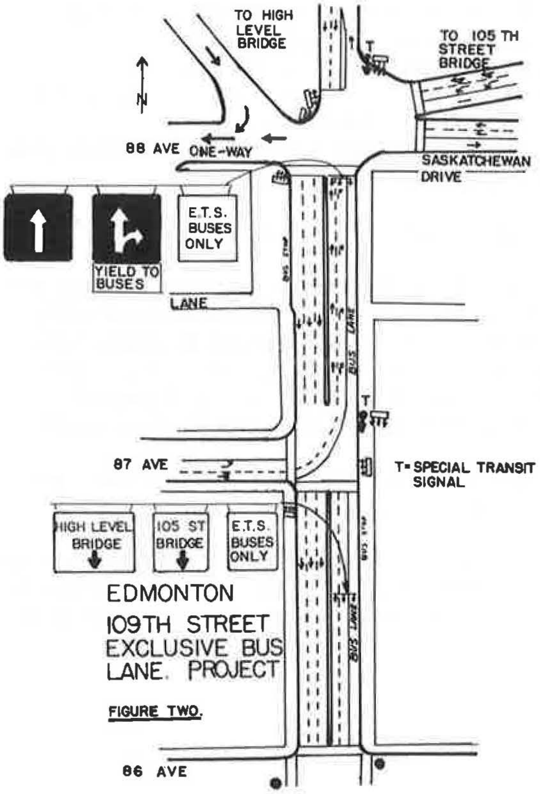
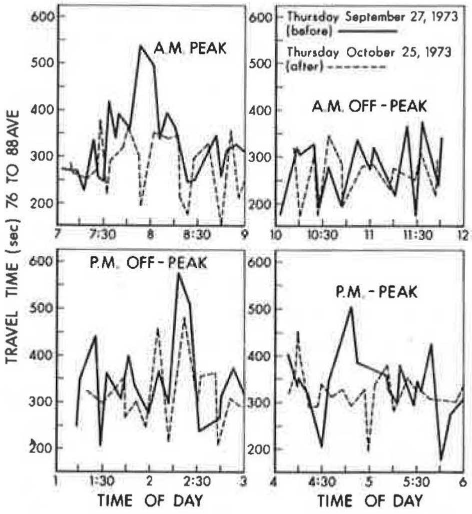


Figure 3. Bus travel times before and after implementation of exclusive bus lane.



HOW TO GIVE PRIORITY TREATMENT

Curb Lane

The exclusive curb lane will work well when (a) there are few right turners, (b) parking can be prohibited, and (c) alternate traffic lanes are available for vehicular traffic.

Because of the circumstances already described, the curb lane operation in Vancouver on Seymour Street (a one-way street) does not work well because too many right turners interfere with the transit movements.

Median Lane Operations

Median lane operation is similar to that for tramways or streetcars and can be used when wide rights-of-way are available. This method should be considered if the city is intending to use lightweight rapid transit since it can be one of a number of intermediate stages in the development of rail rapid transit.

The problems of median lane operation are the transit stops, which must be well designed. Also, left turns generally should either be banned or guided through with separate signals.

Reversed Flow

On One-Way Streets

The operation on Seventh Avenue in Calgary is a good example. This self-enforcing operation has all the advantages and few disadvantages. The major disadvantage is that pedestrians must be made to look both ways before crossing. The other problem arises at the start and finish of this lane.

Cities that contemplate using exclusive bus lanes should view the reversed flow on one-way streets as their first desirable alternative.

On Wrong Side of Median

Reversed flow on the wrong side of a median arises on freeways or wide arterial roads with tidal peak-hour flow. If the traffic lanes (three or more) in the off-peak direction are underused, then one lane next to the median can be reversed. A lane width of 15 to 17 ft (4.5 to 5 m) and traffic cones to separate opposing traffic flows are desirable. There are numerous applications for reversed flow (1).

Exclusive Approach Lane

The exclusive approach lane can be used where the frequency of bus service or the roadway width makes a continuous exclusive bus lane impossible. The method requires widening of the approach at the intersection or having buses use an exclusive right-turn lane to go straight through. If the signal timing plan is combined with the exclusive approach, transit vehicles can be guided through the intersection with priority treatment. The system is particularly valuable where there is a multiphase timing plan. A transit vehicle requires 4 sec for the first vehicle and 2 sec for each subsequent vehicle. The maximum number allowed through depends on the transit stop capacity. For example, in Delft, since only two transit vehicles can be accommodated at the transit stop, the maximum is 6 sec.

Exclusive Transit Signals

There is also a need for separate, exclusive transit signal indications with or without exclusive lanes or approaches. In Edmonton, the yellow T-signal is used, and in Holland a whole series of signals is used. There is a need for standardization here. In Edmonton, the transit signal is placed higher than the normal signal so that the motorist is not confused. At the project on 109th Street, one such signal is located at a T-intersection (87th Avenue is the side street). Bus traffic can proceed after the bus has stopped and pedestrians have crossed the street. The only other restriction is that buses must yield to other buses coming from 87th Avenue and going into the bus lane (Figure 2).

Similar signal indications are used with the bus crossing signal at 57th Avenue and 111th Street. A special transit signal would also be more useful than the normal green indication for reversed flow.

GENERAL APPROACH TO EXCLUSIVE LANES

Data Before Implementation

The difficulty with assessing the effectiveness of exclusive bus lanes is the lack of data about the before situation. The data needed should include

1. Travel time for both transit (Figure 3) and cars,
2. Delay time at intersections for both transit and cars,
3. People volumes of both transit and cars, and
4. Vehicle volumes of both transit and cars.

These data should be supplemented with photographs and film or television tape.

Public Participation Before Implementation

In Edmonton, a public hearing was held before the exclusive lane was installed. Anyone for or against installation could express an opinion about the desirability or nondesirability of an exclusive lane.

The main opposition came from the merchants on the west side of 109th Street, who felt that their businesses would be adversely affected by the all-day banning of left turns on 109th Street for six blocks.

Publicity

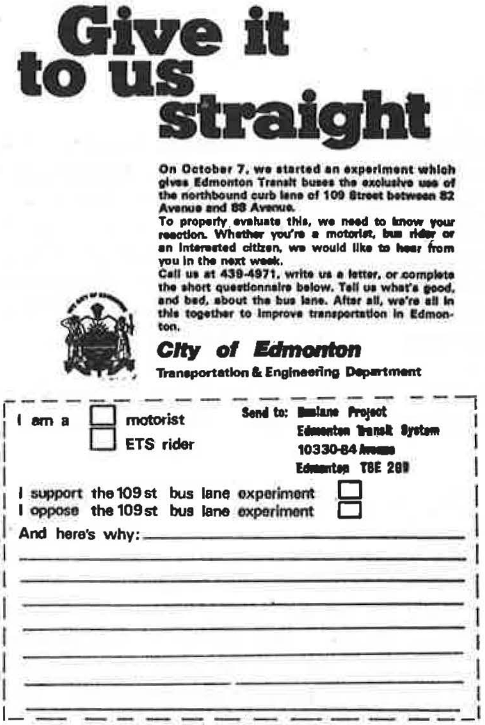
Publicity consisted of advertising in the local newspaper (Figures 4 and 5) and the university newspaper, and 30-sec radio advertisements in the peak driving time were also used. The signing used was overhead signs with one or two sets of lane signs every block. The white-on-black lane signs were used to conform with lane designation signs of the Canadian Uniform Traffic Control Manual.

Additional signs were placed on the side streets to advise motorists to enter into the center lane.

Data After Implementation

The data collected after implementation should include the same type of information as was collected before implementation. These data should be supplemented with photographs and film.

Figure 4. Advertisement before exclusive transit lane implemented.



Give it to us straight

On October 7, we started an experiment which gives Edmonton Transit buses the exclusive use of the northbound curb lane of 109 Street between 82 Avenue and 88 Avenue.

To properly evaluate this, we need to know your reaction. Whether you're a motorist, bus rider or an interested citizen, we would like to hear from you in the next week.

Call us at 439-4971, write us a letter, or complete the short questionnaire below. Tell us what's good, and bad, about the bus lane. After all, we're all in this together to improve transportation in Edmonton.

City of Edmonton
Transportation & Engineering Department

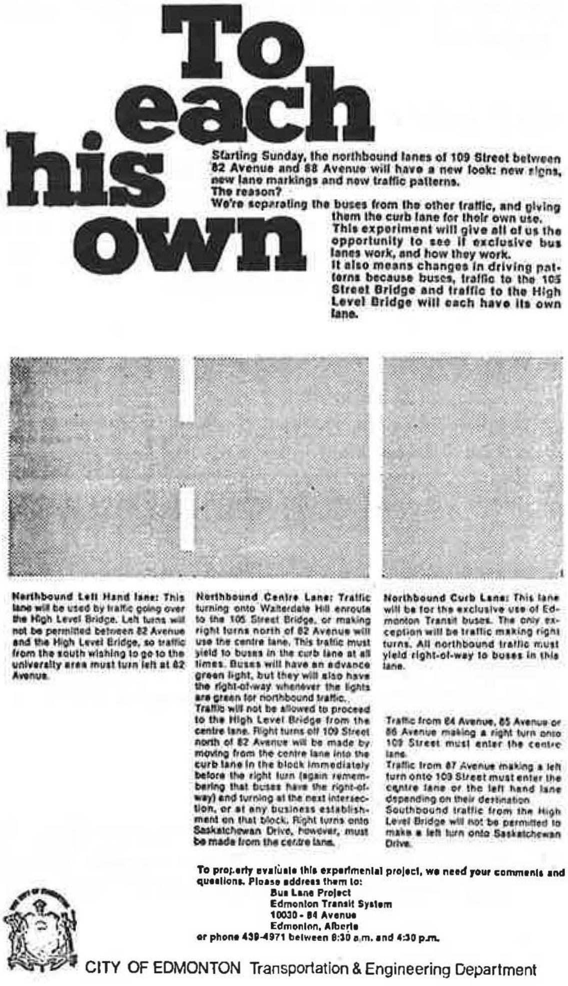
I am a ☐ motorist
☐ ETS rider

Send to: Buslane Project
Edmonton Transit System
10330-84 Avenue
Edmonton T6E 289

I support the 109 st bus lane experiment ☐
I oppose the 109 st bus lane experiment ☐

And here's why: ____________________

Figure 5. Advertisement after bus lane implemented.



To each his own

Starting Sunday, the northbound lanes of 109 Street between 82 Avenue and 88 Avenue will have a new look: new signs, new lane markings and new traffic patterns.

The reason?

We're separating the buses from the other traffic, and giving them the curb lane for their own use.

This experiment will give all of us the opportunity to see if exclusive bus lanes work, and how they work.

It also means changes in driving patterns because buses, traffic to the 105 Street Bridge and traffic to the High Level Bridge will each have its own lane.

Northbound Left Hand lane: This lane will be used by traffic going over the High Level Bridge. Left turns will not be permitted between 82 Avenue and the High Level Bridge, so traffic from the south wishing to go to the university area must turn left at 82 Avenue.

Northbound Centre Lane: Traffic turning onto Walterdale Hill enroute to the 105 Street Bridge, or making right turns north of 82 Avenue will use the centre lane. This traffic must yield to buses in the curb lane at all times. Buses will have an advance green light, but they will also have the right-of-way whenever the lights are green for northbound traffic.

Traffic will not be allowed to proceed to the High Level Bridge from the centre lane. Right turns off 109 Street north of 82 Avenue will be made by moving from the centre lane into the curb lane in the block immediately before the right turn (again remembering that buses have the right-of-way) and turning at the next intersection, or at any business establishment on that block. Right turns onto Saskatchewan Drive, however, must be made from the centre lane.

Northbound Curb Lane: This lane will be for the exclusive use of Edmonton Transit buses. The only exception will be traffic making right turns. All northbound traffic must yield right-of-way to buses in this lane.

Traffic from 84 Avenue, 85 Avenue or 86 Avenue making a right turn onto 109 Street must enter the centre lane.

Traffic from 87 Avenue making a left turn onto 109 Street must enter the centre lane or the left hand lane depending on their destination.

Southbound traffic from the High Level Bridge will not be permitted to make a left turn onto Saskatchewan Drive.

To properly evaluate this experimental project, we need your comments and questions. Please address them to:

Bus Lane Project
Edmonton Transit System
10030 - 84 Avenue
Edmonton, Alberta

or phone 439-4971 between 8:30 a.m. and 4:30 p.m.

CITY OF EDMONTON Transportation & Engineering Department

Evaluation

The evaluation afterwards should include all the agencies and people that were involved in the implementation: the traffic engineers; the police department; the transit operations, particularly the transit inspectors; and the public.

In Edmonton, the public was asked to express a viewpoint. Advertisements were placed in both the Edmonton Journal and the university newspaper. The advertisement in the newspaper asked whether the respondent was a motorist or bus rider, whether he or she supported or opposed the bus lane project, and what reasons there were for their opinions. A log was kept of telephone calls that were received regarding the project.

The final tally was 88 for and 55 against, which means that most people using 109th Street did not react at all. The respondents who were opposed had the following reasons:

1. The no-left-turn lane was in effect all day. As a result, the ban was changed to peak hours only.
2. The right turn was confusing. Initially right turns were allowed from the bus lane, except at 88th Avenue, where the exclusive signal was. The rule was changed to right turns from the center lane, but YIELD to buses along the entire length. Because there are few right turns except at 88th Avenue, this rule has not presented major problems, but a little give and take are still required.
3. There was a lack of enforcement. Because the police were not sure under what bylaw or act enforcement should take place, they gave advice and issued warnings. This worked well. Later, when Edmonton had a transit strike, the police occasionally parked a cruiser in the bus lane so that motorists adopted the habit of not using the bus lane at all.

TIME SAVING

The time saving for buses in the peak period was between 2 and 6 min, and there was a slight reduction in the car travel time.

The main result was, however, that the bus travel time became consistent regardless of traffic conditions. The public's perception of the time saved was far greater than it was possible to measure.

CONCLUSION

Although several exclusive lane experiments have been made, there is a lack of uniform data gathering. New criteria need to be developed about where to use exclusive lanes; the most useful criterion is to determine whether the separation of traffic will reduce the total people hours of travel time.

ACKNOWLEDGMENTS

I would like to gratefully acknowledge the assistance of the city of Edmonton and the Edmonton Transit System for the implementation of the 109th Street bus lane and for permission to use data regarding this bus lane.

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EVALUATION OF A NATIONAL EXPERIMENT IN BUS RAPID TRANSIT

John L. Crain, Bigelow-Crain Associates

An extensive evaluation is being performed of a bus rapid transit system in Los Angeles that uses exclusive bus lanes in the median strip of a freeway. This national experiment is currently quite successful. Operational feasibility has been demonstrated, and the number of busway system riders has continuously grown over the first 18 months of operation even though the facility is only partially operational. The new riders are former automobile users, and their socioeconomic profiles are more similar to automobile commuters than to bus commuters. Assuming that car occupancy is only 1.3 persons/vehicle, the busway system has at least a tenfold greater capacity (per traffic lane) than the highway system. However, the busway lanes during peak periods currently carry only about half of the person trips that are carried by a freeway lane but are catching up fast. The principal causes for travelers switching from automobile to busway commuting, based on survey results, are to save travel time and to avoid the frustration of the stop-and-go characteristics of a congested freeway.

•THE San Bernardino Freeway Express Busway is an 11-mile (17.7-km) double-lane exclusive roadway for buses running east and west from downtown Los Angeles through a middle-income, suburban residential commute corridor. The busway lanes are physically separated by concrete and flexible barriers from those serving the automobile traffic, and this makes it a bus rapid transit system. This $60 million bus rapid transit system is the first such facility in the United States that is complete with online stations and double (bidirectional) bus lanes.

The eastern half of the busway was opened on January 29, 1973. On July 16, the first of its three rapid transit stations was opened at El Monte. This station, at the eastern terminus, is a modern facility complete with parking spaces to provide for automobile park-and-ride service. There are 700 completed spaces now, 700 to be built. The other two stations, one at a hospital and the other at a university, are destination stations and do not have parking facilities.

The San Bernardino Freeway Express Busway experiment and its forerunner, the Shirley Highway Busway in the Washington, D.C., metropolitan area, are of great significance to the national effort to rebuild public transportation. The busway form of rapid transit is a distinct alternative to rail rapid transit and has some apparent advantages. It is less costly to build than a suburban-to-downtown line-haul facility. It can be built quickly in 2 to 5 years; a rail facility would take longer. It is more flexible because the vehicle can leave the fixed right-of-way for collection and distribution. Routes and schedules can be changed easily. Currently, federal financial support is more readily available since federal and (usually) state highway trust fund monies can be used for construction of a busway facility.

The major uncertainty is the handling of the many buses converging on the downtown area. The concept and cost of a grade separation downtown bus distribution system have not been determined and could pose difficulties not present in rail rapid transit. The bus does not have the inherent comfort features of a train: room to move around, large seating area, and smoothness of ride. Finally, many people view the bus as an undesirable alternative to automobile or train riding because of its unreliable schedule, frequent stops and starts, and crowded and uncomfortable conditions.

The major objective of these busway experiments is to determine if the bus when put into a rapid transit form can be found attractive by the riding public. If so, this more flexible and easier to implement form of rapid transit will play a large role in the national effort to rebalance public and private transportation services.

EVALUATION METHODOLOGY

A comprehensive evaluation of the busway is being carried out as a joint effort of the Southern California Association of Governments (SCAG), the Urban Mass Transportation Administration, the Federal Highway Administration, the California Department of Transportation (DOT), the Southern California Rapid Transit District (SCRTD), and the city of Los Angeles. This 5-year effort assesses the operational and economic feasibility and the traveler response to the new facility.

Findings can be related to the other major national busway experiment, the Shirley Highway Busway. Findings are also related to the SCAG short-range transportation plan, by which the Los Angeles basin is to meet federal requirements for transportation planning and environmental protection. Thus, the busway project acts as a pilot demonstration for the busway elements of the short-range plan.

The evaluation is carried out through a variety of ongoing work tasks, which are described and interrelated in the following.

Time Series Analysis

There is a continuous process of monitoring ridership on the busway and traffic counts on the parallel highway. Traffic counts include speed measurements, vehicle counts, and occupancy counts. Approximately every 6 months there are bus ridership and traffic counts throughout the entire corridor served by the busway. These data are plotted in a time series and include identification of events (i.e., process interventions) that might have an effect on ridership and traffic trends.

Household Surveys

Approximately once a year a major household survey is conducted to interview commuters at their doorsteps. These interviews determine which commuters are using which modes and submodes, their socioeconomic profiles, the time and cost of the mode being used, and their reasons for using the present mode (why they have switched, if they have, and their attitudes toward and perceptions of the busway). A small, clustered random sampling process is used with a 6-min interview. This method reduces data collection costs to a few dollars per completed interview but enables a comprehensive cross-sectional analysis of the corridor to be obtained.

On-Board Surveys

About once every 2 years, a comprehensive on-board survey is performed of busway users. These surveys supplement the household survey results with data, based on a large sample, on socioeconomics and attitude-perceptions and origin-destinations of busway users.

Cost Analysis

A comprehensive cost analysis is performed of capital and operating costs of the busway. This includes an assessment of the impact of the faster busway operations on vehicle and personnel use.

Market Analysis

From the survey results, the central market analysis is performed. A cost analysis is made of the mode not used so that the cost difference (disutility value) can be attached to each commute trip in the sample. The final analysis output is a measure of transit market share throughout the corridor served and of how patronage and market share are affected by various factors.

Modal Split Analysis

Finally, the survey results are put into the traditional modal split framework so that a modal split curve can be obtained and compared with the curve used for rapid transit planning throughout the Los Angeles basin.

RESEARCH FINDINGS

During the first 18 months of busway operation, when the data discussed were collected, only the eastern two-thirds of the busway and the El Monte station were operational, and most of the time there was no special handling of busways in downtown Los Angeles. Exclusive downtown lanes were incorporated and the western third of the busway was completed in the spring of 1974. The two on-line stations will be opened in September 1974. Figures 1 and 2 show some of the features of the busway.

Public Acceptance

After 18 months of operation, there appears to be a warm acceptance of the busway concept by users and nonusers alike. The 1973 spring survey showed that residents of 82 percent of commuter households and 76 percent of noncommuter households were aware of the busway. By the fall survey, these numbers had changed to 86 percent and 73 percent and were highest, 92 percent and 78 percent, in the corridor area east of El Monte where busway service was already available.

Of all commuters interviewed during the fall household survey, 75 percent offered general praise of the busway (e.g., it will reduce pollution and improve total freeway efficiency). About 20 percent were negative (e.g., busway lanes are wrong, unsafe, too costly).

Operational Feasibility

The operational feasibility of the busway system has been conclusively demonstrated. Buses have operated over the busway successfully and reliably. Automobiles have not invaded the exclusive bus lanes. To date, there have been no accidents attributable to the existence of the busway.

SCRTD has mastered the problems of rerouting and rescheduling to incorporate the new busway into their total system. The innovative El Monte station and park-and-ride facility has functioned without major customer problems since its opening.

Ridership Growth

Commuters have responded favorably to the busway, and the ridership on the busway transit lines has risen dramatically (Table 1). A time series graph of this ridership compared with ridership growth of the Shirley Highway Busway is shown in Figure 3.

This growth has also been measured in terms of market share. The transit market is defined as the total of all commuters who live within the San Bernardino Freeway

Figure 1. San Bernardino Freeway Busway.

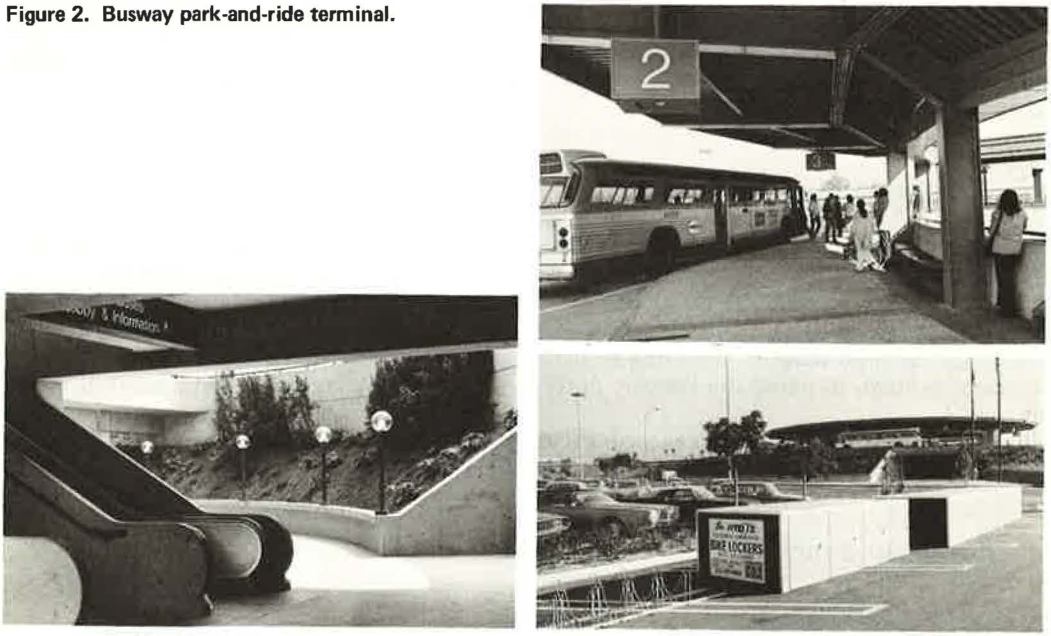
Table 1. Ridership growth on San Bernardino Freeway Express Busway.

Time	Riders	
	Peak[a]	Off-Peak[b]
January 1973	1,200	800
April 1973	1,250	750
September 1973	2,500	1,200
December 1973	4,000	1,600
June 1974	7,500	3,000

[a] 5.5-hour period of morning inbound and evening outbound traffic.

[b] Between 6 a.m. and 8 p.m., both directions.

Figure 2. Busway park-and-ride terminal.



corridor in areas that are or will be served by the busway and who regularly commute to the Los Angeles area. The transit share of this market during 1973 has risen from 12 to 16.5 percent. More important, the transit market share of the eastern portion of the corridor that was served by the busway in 1973 has risen from about 4 to 25 percent.

Comparison of Highway and Busway

Because busway patronage is still growing, one cannot yet compare highway and busway volumes. The number of bus runs operating over the busway was quadrupled with the opening of the El Monte station. Although patronage has risen dramatically, it has not yet caught up with this greatly increased supply of service. Similarly, the inbound busway lane is currently carrying only about two-thirds as many people as adjacent automobile lanes.

As the many additions to the busway are incorporated in the coming phases, busway ridership will hopefully surpass that of the parallel highways. Although measurements of capacity have not yet been taken, this report suggests that the busway capacity will be at least 14,000 riders/hour. Assuming the current 1.3 persons/automobile, this is more than five times larger than the capacity of a highway lane.

Of course, there is no rationality in suggesting that the busway lane should carry the same number of rush-period trips as one of the parallel highway lanes. The busway lane costs more to build and to operate but produces many more benefits in terms of reduced air pollution, conservation of energy, and fewer traffic accidents. At some volume, the busway will be equal to the competing highway lane in terms of benefits and costs.

Causes of Busway Ridership Growth

During the 1973 period when most of this analysis was performed, the busway was in only a partially completed state. At that time, the busway service was only about 5 to 7 min faster than automobile commuting. This small time savings was only obtainable through the park-and-ride and kiss-and-ride modes (the upsurge in use of these two modes represented most of the busway patronage growth). There were essentially no monetary savings in using the busway until the low ($0.25) fare was incorporated in early 1974.

Following are the primary reasons given by those who have switched over to the busway mode and the percentage ranking for the various reasons:

Reason for Switching	Percent
Time, convenience	46
Frustration with automobile	18
Cost savings	14
Employment change	9
No reason given	9
Other	4

The parallel freeway lanes are operating at capacity with traffic slowed to 30 to 35 mph (48 to 56 km/h) most of the time. It is important that busway ridership growth is linked to congestion on the freeway. If the congestion were reduced by increasing highway capacity, the primary stated reason for switching modes would be removed. Thus, the growth in busway ridership would probably be halted and possibly reversed.

New Transit Users

Traditionally, there has been a significant difference in the socioeconomic characteristics of automobile and transit commuters. Transit commuters have tended to be more often female, have less income, and be more limited by automobile availability. The data in Table 2 give a profile of the new people being drawn to the busway system and indicate that they tend to more closely resemble the automobile commuter than the traditional bus user.

The data for busway users (Table 2) are based on a small sample of interviewees, but the differences between these data and the data on prebusway transit users are, in general, statistically significant.

Modal Split Implications

One purpose of the busway evaluation is to provide a check, based on marketplace conditions, of the modal split curves now being used in rapid transit planning in the Los Angeles area. This check now appears to be somewhat inconclusive; the modal split values obtained from interviews of >600 commuter households are about five percentage points higher than those values currently being used for planning (Figure 4).

The disutility function (against which the modal split value is plotted) represents the differential in total cost in dollars between commuting by transit and by automobile. The cost for each mode includes the travel time, valued at one-fourth of the traveler's wage rate; excess time (waiting for or walking to or from vehicles), valued at a rate 2.5 times higher than riding time; and all economic costs. The survey procedure includes a detailed accounting of parking costs, car-pool payments, and receipts. The difference in this total cost between the two modes is the disutility value. Where this value shows transit to be better (i.e., less costly), the transit modal split should be high (Figure 5).

The San Bernardino Freeway corridor seems to have a relatively higher transit modal split than other sectors of the Los Angeles basin. There are distinct reasons why the transit modal split values might be higher in this corridor. Bus service in this corridor has always been maintained at a high level and has always been well patronized. The prebusway, 1972 on-board survey revealed that about one-third of all bus commuters in this corridor were using the bus by choice rather than by necessity. Approximately 40 percent of these commuters had selected their residential location in proximity to bus service. This long-term institutional relationship between commuter and bus service tends to keep the transit market share value high. Thus, the busway service was introduced to an area where transit had enjoyed a good image for years.

Attitudes

The evaluation has proved conclusively that there is an attitudinal factor that affects the modal choice decision process, and this factor is as important, in terms of effect, as travel time and travel cost savings. Figure 5 shows the modal split curve (Figure 4) for subsets of the survey population who revealed positive and negative attitudes toward transit. These subsets are based on the degree of agreement or disagreement with the following attitudinal statements:

1. If new, improved, and convenient public transportation service were introduced, I would certainly use it; and
2. I hate to be tied to fixed schedules for traveling.

These curves show that those people who indicated positive attitudes have a higher tendency to use transit at all disutility values; however, caution must be used in interpreting these attitudinal data. Some of the people may be using transit for reasons not related to attitude but may be exhibiting a positive attitude to rationalize their

Figure 3. Busway ridership trends.

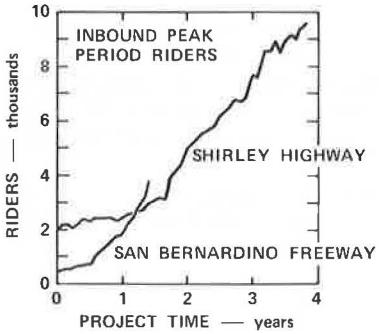


Figure 4. Check of modal split model.

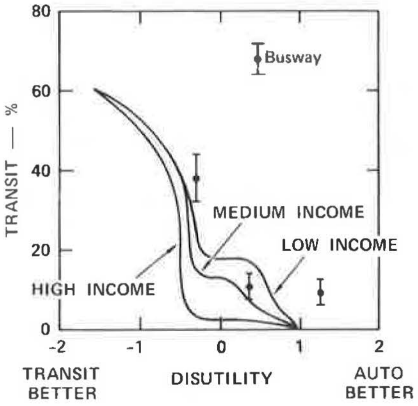
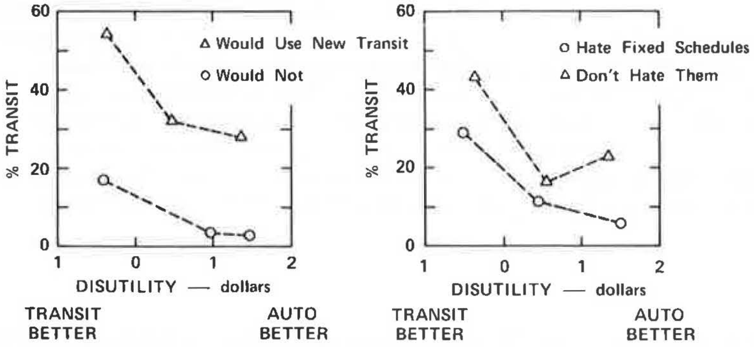


Table 2. Commuter profiles.

Description	Automobile Users (percent)	Busway Users (percent)	Prebusway Transit Users (percent)
Female	51	52	65
Income < $10,000	21	18	54
Over 40 years	40	36	55
Cars per household ≤ 1	25	40	NA

Figure 5. Modal split versus attitude.



commuting behavior. Some of the people responding negatively to the first attitudinal statement are not exhibiting an attitudinal response but are explaining that they cannot use transit regardless of its qualities (they must take their cars to work because they use them during the day). Twenty-four percent of the automobile commuters interviewed claimed they needed their car at their place of work.

Notwithstanding these reservations on the meaning of the attitudinal data, attitude is a major factor in modal split, and much more research is needed in this area, particularly as it relates to marketing transit.

Busway Compared With Rail Rapid Transit

The comparison of the busway and rail rapid transit is critically important to southern California because of the required large investment costs for rapid transit. It is premature to draw this busway-rail comparison, but at this point it is clear that this particular busway does not appear to be inferior to rail rapid transit in its ability to attract passengers. This statement cannot be generalized to other busways. The success in patronage growth of this busway must be noted relative to (a) the type of service provided (suburb-to-downtown), (b) the demand level, and (c) the comparatively large transit market share traditionally enjoyed by SCRTD in this corridor.

FUTURE PHASES

We have now completed phase 1 of the busway experiment, exclusive use by transit vehicles of the partial busway. Phase 2 will commence when the completed busway with all three stations becomes operational in September 1974. Buses will continue to be the sole user of the busway during the 2-year phase 2 program. In the 3-year phase 3 program, the current California DOT-SCRTD agreement calls for experimentation in which car pools are metered for travel on the busway lanes.

The final plans for phase 3 as well as decisions on the use of the busway concept in other Los Angeles corridors and in other corridors throughout the nation will depend on the continuing findings of the San Bernardino Freeway Express Busway evaluation.

BUS CAPACITY ANALYSIS

William F. Hoey and Herbert S. Levinson, Wilbur Smith and Associates

This paper provides an initial input for updating the section on bus capacity in the Highway Capacity Manual and identifies parameters, principles, and procedures for estimating the capacity of bus facilities and systems. It reviews available data on bus capacities, suggests design assumptions for bus system planning and analysis, and outlines further research needs. The studies demonstrate that (a) the critical element governing system capacity is the bus station platform or bus stop rather than the busway; (b) at stations, capacity is determined by the number of door channels on the bus and fare collection practices; and (c) bus capacity should be viewed in terms of people transported rather than buses moved per hour.

•BUS capacity values differ widely according to the basic type of operation: in terminals, on arterial streets, or along exclusive busways. This paper concentrates on capacity analysis of bus lanes and busways because terminal capacity depends heavily on the specific mode and pattern of operation (i.e., extent of intercity operations, layover times, and fare collection practices). Results of previous studies are summarized, basic analytical relationships are presented, and capacity ranges and planning guidelines are suggested in an effort to update previous reports (1, 2). The ability of buses to move people under preferential conditions is examined; that is, the impedance of other vehicles in mixed traffic is not considered quantitatively.

PREVIOUS STUDIES AND EXPERIENCES

The number of buses that can operate past a point in a given period of time varies widely according to specific roadway and operating conditions. Previous theoretical studies and actual operating experience provide the basis for subsequent analyses.

Theoretical Values

Ranges in bus capacities or volumes based on theoretical studies are given in Table 1 (3). These studies have primarily investigated the effect of buses on the capacity of mixed traffic roadways (4, 5). When buses do not stop, bus lane capacity is essentially that of equivalent passenger cars. Thus, assuming normal freeway vehicle headways, theoretical capacities of ≥900 buses/lane/hour could be achieved on exclusive bus roadways with uninterrupted flow.

Theoretical simulation studies, based on buses that have 30-sec dwell times and that operate in platoons of six between stations 0.3 mile (0.5 km) apart, result in capacities ranging from 350 to 400 buses/hour on an exclusive grade-separated busway (6).

Operational Experience

Observed bus volumes on heavily used freeways and city streets are given in Table 2 (3). The highest volumes, 735 buses/lane/hour in the Lincoln Tunnel and on the Port Authority Bus Terminal access ramp, are achieved on a completely exclusive right-of-way where vehicles make no stops. Where bus stops or layovers are involved, reported volumes are much less.

Table 1. Theoretical bus volumes.

Source or Facility	Buses per Hour	Headway (sec)	Average Bus Stop Spacing (ft)	Average Bus Speed (mph)	Equivalent Passengers per Hour[a]
General Motors Proving Ground					
Uninterrupted flow	1,450[b]	2.5	No stops	33	72,500
Highway Capacity Manual					
Freeway level of service D	940	3.8	No stops	33	47,000
Freeway level of service C	690	5.2	No stops	40 to 60	34,500
General Motors Proving Ground					
Six-bus platoons, 30-sec on-line stops	400	9.0	Variable	15 to 20	20,000
1965 Highway Capacity Manual					
Arterial streets, 25-sec loading and 25-sec clearance	72	50	Not cited	Not cited	3,600
Toronto Transit Commission					
Planning criteria	60	60	500 to 600	10	3,000

Note: 1 ft = 0.3 m. 1 mph = 1.6 km/h.

[a] 50 passengers/bus.

[b] Subsequent studies have reported bus volumes of 900 to 1,000 vehicles/lane/hour; these are consistent with reported flows.

Table 2. Observed bus volumes.

Facility	Buses per Hour	Headway (sec)	Average Bus Stop Spacing (ft)	Average Bus Speed (mph)	Equivalent Passengers per Hour
Lincoln Tunnel—uninterrupted flow	735	4.9	No stops	30	32,560
I-495 (New Jersey) exclusive bus lane—uninterrupted flow	485	7.3	No stops	30 to 40	21,600
San Francisco-Oakland Bay Bridge	350	10.3	No stops	30 to 40	13,000
South Michigan Avenue, Chicago—5-min rate and some multiple lane use	228	16	Not cited	Not cited	11,400[a]
Hillside Avenue, New York City—multiple lane use and lightly patronized stops	170	21	530	Not cited	8,500[a]
Shirley Highway Busway and Fourteenth Street bus lanes	160	23	900[b]	35[c] 6 to 12[b]	8,000[a]
State Street, Chicago; Market Street, Philadelphia; and Market Street, San Francisco—multiple lanes	150	24	300 to 600	6 to 10	6,100 to 9,900
K Street, Washington, D.C.	130	28	500	5 to 8	6,500[a]
Downtown streets in various cities—single lane with stops	90 to 120	30 to 40	500	5 to 10	4,500 to 6,000[a]

Note: 1 ft = 0.3 m. 1 mph = 1.6 km/h.

[a] 50 passengers/bus. [b] In CBD. [c] On freeway.

Bus Stops

Stopping a bus to pick up or discharge passengers limits the capacity of a bus lane. Time must be allowed for acceleration, deceleration, stop clearance, and periods when the doors are open. Observed volumes for lanes with intermediate stops rarely exceed 120 buses/hour, although volumes of ≥180 buses/hour are feasible where buses use two or more lanes and where stopped vehicles can be overtaken if there is careful management and control of bus operations. [Maximum streetcar volumes on city streets 50 years ago approached 150 cars/track/hour when there was extensive queuing and platoon loading at heavy stops (7).]

Busways

The only existing example of a downtown grade-separated busway is in Runcorn, England; this busway operates well within its potential capacity. The intermediate stations on the San Bernardino Freeway Busway in Los Angeles are off-line; the El Monte station of the busway operates as a terminal, and downtown Los Angeles distribution is by on-street bus lanes. Volumes approach 80 buses/hour on the busway.

BERTH CAPACITY FOR BUSES

Reviewing experience suggested that theoretical analysis of bus stop and station operation could be useful for estimating realistic capacities of busways.

Basic Variables and Relationships

The number of buses per lane per hour and the number of people they carry depend on the following:

1. The roadway or guideway, for which capacity depends on the number of lanes, their occupancy, signalization, and flow restrictions (or interferences);
2. The vehicle, for which capacity depends on its size and internal circulation capability;
3. The interface between buses and pedestrians at a bus station platform or bus loading zone, for which capacity depends on the number and organization of boarding and alighting channels; and
4. The required clearance times between buses.

Various analytical relationships were derived to show how these factors influence the capacity of a downtown busway. The analyses establish ranges in typical time requirements for each of the sequent operations at a bus berth and identify relationships among bus passenger line-haul capacity, boarding and alighting volumes, and major parameters or equipment and facilities. They focus on the peak 10 to 15 min in the rush hour, since this time period usually represents the maximum boarding (or alighting) volumes and the maximum line-haul loading.

The basic variables used in the analyses are given below.

A = alighting passengers per bus in peak 10 to 15 min;
a = alighting service time in seconds per passenger;
B = boarding passengers per bus in peak 10 to 15 min;
b = boarding service time in seconds per passenger;
C = clearance time between successive buses in seconds (time between closing of doors on first bus and opening of doors on second bus);
D = bus dwell time at a stop in seconds per bus (time when doors are open and bus is stopped);
f = bus frequency in buses per hour (all routes using a facility) at maximum load point (if all buses stop at all stations, f = number of effective berths $\times f'$);
h = bus headway on facility in seconds at maximum load point, $3,600/f$;
f' = maximum peak bus frequency at a berth in buses per hour;
h' = minimum bus headway at a berth in seconds, $3,600/f'$;
G = boarding passenger capacity per berth per hour;
H = alighting passenger capacity per berth per hour;
J = passengers boarding per hour at heaviest stop or maximum load point;
K = passengers alighting per hour at heaviest stop or maximum load point;
L = peak-hour load factor in passengers per bus seat per hour at the maximum load point;
N = number of effective berths at a station or bus stop, i.e., $(N')(u)$;
N' = number of berth spaces provided in a multiberth station;
P = line-haul capacity of bus facility in total persons per hour past the maximum load point (hourly flow rate based on peak 10 to 15 min);
S = seating capacity of bus, varies with design;
u = berth use factor (an efficiency factor applied to total number of berths to estimate realistic capacity of a multiberth station, i.e., N/N');
X = percentage of maximum load-point passengers boarding at heaviest stop, J/P; and
Y = percentage of maximum load-point passengers alighting at heaviest stop, K/P.

Equations for the basic relationships for a single station are as follows:

$$h' = Bb + C \tag{1}$$

$$f' = \frac{3{,}600}{h'} = \frac{3{,}600}{Bb + C} \tag{2}$$

$$G = f'B = \frac{3{,}600B}{Bb + C} \tag{3}$$

$$N = \frac{J}{G} = \frac{J(Bb + C)}{3{,}600B} \tag{4}$$

$$f = f'N = \frac{J}{B} \tag{5}$$

The capacity of any system is governed by the number of passengers (a) boarding or alighting at the heaviest stop or (b) traveling past the maximum load point (between stops), whichever is less. Accordingly, equations 6 through 10 show how maximum load point and heaviest station parameters relate. These relationships assume that loading conditions govern; a similar set of equations could be derived on the assumption that passenger alighting (or passenger interchange) governs.

$$f = \frac{P}{S} \tag{6}$$

$$B = X(S) \tag{7}$$

$$h' = bB + C = X(S)b + C \tag{8}$$

$$f' = \frac{3{,}600}{h'} = \frac{3{,}600}{X(S)b + C} \tag{9}$$

$$N = \frac{f}{f'} = \frac{P}{S}\left[\frac{X(S)b + C}{3{,}600}\right] = \frac{P[X(S)b + C]}{3{,}600S} \tag{10}$$

The sequence of analyses is as follows:

1. Maximum load-point demand establishes bus frequency requirements in the corridor;
2. Bus frequency and boarding volumes determine minimum headway per berth (for planned systems, where no boarding counts are available, the percentage of passengers boarding at the heaviest stop is a key parameter of total passenger capacity);
3. The maximum bus frequency per berth depends on this minimum headway; and
4. Berth needs are derived from the required bus frequency at the maximum load point and the maximum bus frequency that can load at the heaviest berth.

Assuming that boarding conditions govern, the analytical approach leads to the following equation:

$$P = \frac{3,600\ NS}{bB + C} \tag{11}$$

Or since the variable of boarding passengers per bus depends on bus frequency f,

$$P = \frac{3,600\ N}{Xb + C/S} \tag{12}$$

This relationship can also be expressed in terms of the passenger capacity per berth as follows:

$$P = \frac{NG}{X} = fS \tag{13}$$

These equations indicate that the number of bus berths required at the heaviest stop varies directly with the total passengers to be served at that point, the boarding and alighting service times required per passenger, and the clearance times between buses.

Bus system capacities can be increased (or alternatively berthing requirements can be reduced) by (a) increasing the number of downtown stations, thereby reducing the number of boarding and alighting passengers at the heaviest stop; (b) reducing the loading and unloading times for passengers through multiple doors on buses, prepayment, or selective separation of loading and unloading; and (c) using larger buses to reduce the clearance interval time losses between successive vehicles. In summary, the person capacity of a bus lane appears to depend greatly on the number of doors per bus and the methods of fare collection.

Parameter Estimation

Application of the preceding relationships requires estimating key parameters and providing necessary safety factors.

Bus Headways

The minimum headway of a stop consists of the station dwell time, when the bus doors are open for boarding and alighting, and clearance times between buses.

Field observations of clearance times are limited. A British study (9) reported a dead time (standing at a stop with the doors closed) of 2 to 5 sec. Scheel and Foote (8) indicate that bus start-up times (the time, depending on acceleration and traffic conditions, for a bus to travel its own length after starting ranges from 5 to 10 sec) should also range from 2 to 5 sec. Accordingly, clearance time per bus is estimated at 10 to 20 sec.

Station Dwell Times

Station dwell times may be governed by boarding demand (e.g., in the p.m. peak when substantially empty buses arrive at a heavily used stop), alighting demand (e.g., in the a.m. peak at the same location), or total interchanging passenger demand (e.g., at a major transfer point on the system). In all cases, dwell time is proportional to boarding or alighting volumes times passenger service time.

Observed ranges in passenger service times for various procedures for bus operation and fare collection are given in Tables 3 (11, 12) and 4 (2, 10) for both American and European experience (9).

Boarding service times are usually greater than alighting times. However, some of the equations for stop time in Table 3 relate to total passenger interchange. Differences among cities reflect door configurations, fare collection practices, and one-person versus two-person operations. Some equations reflect the time losses resulting from opening and closing doors (13).

American experience with single-door buses shows passenger boarding times ranging from 2 sec for single-coin fares to >8 sec for multiple-zone fares collected by the driver (Table 5). Alighting times range from about $1\frac{1}{2}$ to $2\frac{1}{2}$ sec for typical urban conditions to ≥6 sec when baggage is involved.

Suggested ranges in bus service times in relation to door width, methods of operation, and fare collection practices are given in Table 5 (2, 3). These bus service times, based on current experiences, were subsequently used to derive relationships between bus and person capacity. They assume that prepayment before entering buses would reduce passenger service times.

Passenger Service Times

Passenger service times decrease as the number of door channels available to passengers increases. The time values in Table 5 reflect the inefficiencies in using additional doorway capacity. For example, one passenger may occupy a double door, and passengers do not distribute themselves uniformly among doorway openings. The time values, however, do not reflect doorway and aisle turbulence at points of heavily simultaneous boarding and alighting.

Figure 1 shows how berth capacity can be increased by changing downtown fare collection practices on a standard versus an urban transit bus. The example shown in Figure 1 is based on the following assumptions: clearance interval, 15 sec/bus; service time with single-coin fare, 3 sec; service time with double doors and prepaid fare, 1.2 sec; and volumes, 10- to 15-min peak flow rates, stated in hourly terms (i.e., with no peak-hour factor). Figure 1 also indicates how increasing the number of passengers boarding per bus tends to decrease frequency of buses that can load at a berth. If the boarding passenger volumes are distributed over several stops so that peak boarding averages 10 passengers/bus at the heaviest stop, from 80 to >140 buses could be scheduled, depending on fare structure, door availability, and the number of alighting passengers. At outlying stops where boarding or alighting averages less than 5 passengers/bus, >120 buses/berth/hour can be scheduled when single-coin fare and single-door entry are used. Conversely, where the entire bus fills up at a given stop, only 20 to 48 buses/hour could be served.

Theoretical Berth Capacities

The theoretical bus berth capacities in persons per hour resulting from the preceding bus analyses are given in Table 6. The following conclusions can be made:

1. Conventional bus loading through a single front door and a single-coin fare would limit berth capacity to a maximum of approximately 1,000 persons/hour;
2. Prepayment of fares and the use of two doors result in berth capacities of 1,500 to 2,400 persons/hour; and
3. Prepayment of fares with 4 doorway channels/bus could result in berth capacities of 2,500 to 3,400 persons/hour.

Table 3. Bus boarding and alighting times in selected urban areas.

Location	Boarding and Alighting Method	Fare Type	Fare Method of Collection	Boarding and Alighting Relationships[a]
Louisville, Kentucky	Alighting only	Flat	Driver	$T = 1.8 + 1.1\ F$
	Boarding only	Flat	Driver	$T = -0.1 + 2.6\ N$
	Simultaneous	Flat	Driver	$T = 1.8 + 1.0\ F + 2.3\ N - 0.02\ FN$
London, England	Consecutive	Graduated	Conductor[b]	$T = 1.3 + 1.5\ (N + F)$
	Consecutive	Graduated	Driver	$T = 8 + 6.9\ N + 1.4\ F$
	Simultaneous	Flat, single-coin	Mechanical	$T = 7 + 2.0\ N$
		Flat, two-coin	Mechanical	$T = 5.7 + 3.3\ N$ - Peak, $T = 5.7 + 5.0\ N$ - off-peak
Toronto, Canada	Simultaneous	Zonal	Fare box	$T = 1.7\ N$, $T = 1.25\ F$, $T = 1.4\ (N + F)$
Copenhagen, Denmark	Simultaneous	Flat	Split entry, driver and machine	$T = 2.2\ N$
Dublin, Ireland	Consecutive	Graduated	Conductor[b]	$T = 1.4\ (N + F)$
	Consecutive	Graduated	Driver	$T = 6.5\ N + 3.0\ F$
Bordeaux, France	Simultaneous	Flat	Driver	$T = 15 + 3\ N$
Toulouse, France	Simultaneous	Flat	Driver	$T = 11 + 4.6\ N$
Paris, France	Simultaneous	Graduated	Driver	$T = 4 + 5\ N$
	Simultaneous	Graduated	Conductor[b]	$T = 2.3\ N$

[a] T = stop time in seconds, N = number of passengers boarding, and F = number of passengers alighting for each bus. These variables do not correspond to those given in this paper.

[b] Buses are operated by two people; all others by one person.

Table 4. Passenger service times on and off buses.

Operation	Conditions	Time (sec)
Unloading	Small amount of hand baggage and parcels and few transfers	1.5 to 2.5
	Moderate amount of hand baggage or many transfers	2.5 to 4
	Considerable baggage from racks (intercity runs)	4 to 6
Loading[a]	Single coin or token fare box	2 to 3
	Odd-penny cash fares, multiple zone fares	3 to 4
	Prepurchased tickets and registration on bus	4 to 6
	Multiple zone fares and cash, including registrations on bus	6 to 8
	Prepayment before entering bus or payment when leaving bus	1.5 to 2.5

[a] Add 1 sec where fare receipts are involved.

Table 5. Bus passenger boarding and alighting service times for selected bus types.

Bus Type	Available Doors or Channels Number	Available Doors or Channels Location	Boarding Times[a] (sec) Prepayment[b]	Boarding Times[a] (sec) Single-Coin Fare[c]	Alighting Times (sec)
Conventional	1	Front	2.0	2.6 to 3.0	1.7
	1	Rear	2.0	—	1.7
	2	Front	1.2	1.8	1.0 to 1.2
	2	Rear	1.2	—	1.0 to 1.2
	2	Front and rear[d]	1.2	—	0.9
	4	Front and rear[e]	0.7	—	0.6
Articulated	3	Front, rear, center	0.9[e]	—	0.8
	2	Rear	1.2[f]	—[f]	—
	2	Front and center[d].	—	—	0.6[f]
	6	Front, rear, center[g]	0.5	—	0.4
Special single unit	6	Three double doors[h]	0.5	—	0.4

[a] Interval between successive boarding or alighting passengers. Does not allow for clearance times between successive buses or dead time at stop.

[b] Also applies to payment-on-leaving or free-transfer situations.

[c] Not applicable with rear-door boarding.

[d] One each.

[e] Less use of separated doors for simultaneous loading and unloading.

[f] Double-door rear loading with single exits, typical European design. Provides one-way flow within vehicle, reducing internal confusion. Desirable for line-haul, especially if two-person operation is feasible. May not be best configuration for busway operation.

[g] Two double doors each.

[h] For example, Neoplan TR-40 Mobile Lounge for airport apron use.

Figure 1. Bus berth capacities versus passenger boarding volumes.

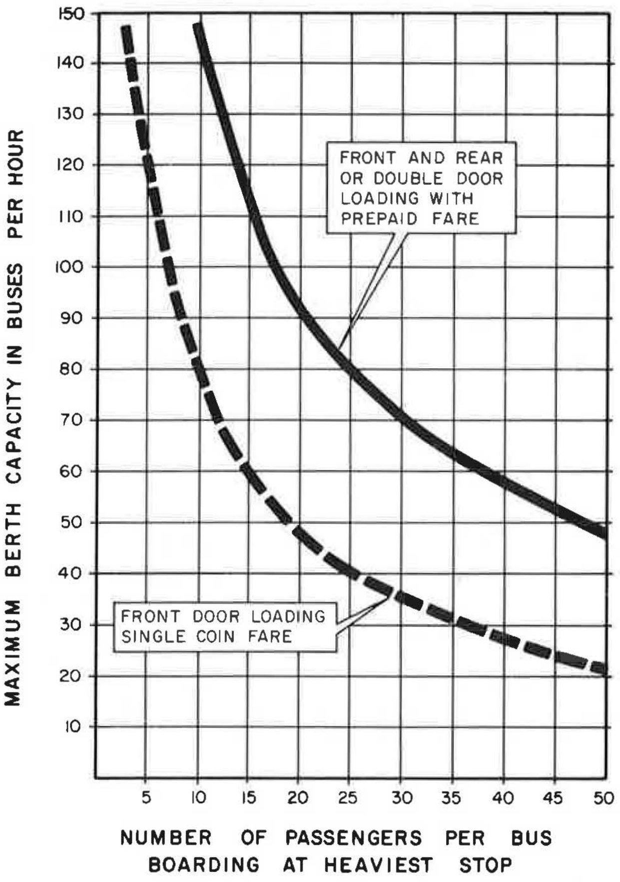


Table 6. Theoretical bus berth capacities related to door channels and fare collection.

Frequency (buses/hour)	Bus Capacity[a] (persons/hour)	Total Clearance Time[b] (sec/hour)	Total Available Dwell Time[c] (sec/hour)	Berth Boarding Capacity (passengers/hour): Single-Coin Fare, 1 Front Door[d]	Berth Boarding Capacity (passengers/hour): Fare Pre-payment, 2 Doorways[e]	Berth Boarding Capacity (passengers/hour): Fare Prepayment, 4 Doorways[f]
20	1,000	300	3,300	—[g]	—[g]	—[g]
30	1,500	450	3,150	1,050	—[g]	—[g]
40	2,000	600	3,000	1,000	—[g]	—[g]
50	2,500	750	2,850	950	2,375	—[g]
60	3,000	900	2,700	900	2,250	—[g]
70	3,500	1,050	2,550	850	2,125	—[g]
80	4,000	1,200	2,400	800	2,000	3,430
90	4,500	1,350	2,250	750	1,875	3,210
100	5,000	1,500	2,100	700	1,750	3,000
110	5,500	1,650	1,950	650	1,625	2,790
120	6,000	1,800	1,800	600	1,500	2,570
130	6,500	1,950	1,650	550	1,375	2,360
140	7,000	2,100	1,500	500	1,250	2,140
150	7,500	2,250	1,350	450	1,125	1,930

[a] 50 passengers/bus. This rate is usually 30 to 70 percent above achievable peak-hour volume because of passenger load variation within the peak hour.
[b] Clearance interval of 15 sec/bus.
[c] 3,600 sec less clearance time.
[d] 1 passenger/3.0 sec.
[e] 1 passenger/1.2 sec.
[f] 1 passenger/0.7 sec.
[g] Single-berth capacity exceeds bus capacity.

Adjusted Berth Capacities

Adjusted berth capacities should be reduced in planning and design to allow for random variations in bus arrivals and for boarding and alighting passenger turbulence. A 25 percent reduction is suggested in applying these factors. Typical resulting values are about 750 passengers/berth/hour for single-coin fare and one-door loading; 1,500 passengers/berth/hour for prepayment and two-door loading; and 2,100 passengers/berth/hour for prepayment and four-door loading.

Berth Use Factors

Bus route schedules may not permit an even distribution of scheduled buses among berths or an even distribution of passengers among loading positions. Further research is necessary to develop typical use factors because experience with high-volume exclusive bus facilities is limited. The use factors in Table 7 (14) are suggested as a guideline.

Bus Use

The number of people per bus will depend on (a) the size of vehicles (50 seats/conventional bus and 60 seats/articulated bus) and (b) operating policies with regard to standees. To provide an acceptable level of comfort for express bus commuters and a minimum nonstop run of 3 to 5 miles (4.8 to 8 km), the load factor in the peak 10- to 15-min period should not exceed 1.00; i.e., there should be a seat available for each passenger. (Higher load factors are acceptable on short, local bus routes.) When total hourly flows are considered, a lower load factor should be assumed, and, depending on land use and work schedules, load factors of 0.6 or 0.7 may not be unreasonable. Such a conservative load factor also will minimize on-vehicle turbulence at bus stops.

Passenger Distribution at Downtown Stops

A reasonable design assumption is that 50 percent of the maximum load-point volume is served at the heaviest downtown stop, assuming a minimum of three stops in the CBD. (The Washington Street-State Street subway station in Chicago accounts for about half of all boarding passengers at the three downtown stops on the State Street line.)

GUIDELINES AND IMPLICATIONS

Suggested busway capacity guidelines for central urban areas are shown in Figure 2 and given in Table 8 for a variety of bus types and service conditions. Figure 2 shows how door configuration and number of berths increase maximum load-point capacity. The left vertical scale applies to typical through-station operations; the right scale applies to a single-station situation.

Table 8 gives the steps and assumptions used in deriving capacities. These computations assume that

1. Passengers per bus at maximum load point is 50 for conventional buses and 60 for articulated buses,
2. Fifty percent of the maximum load-point passengers board at the heaviest CBD stop,
3. There are three loading berths for both on-line and off-line boarding (for alternate station sizes, see Figure 2),
4. An adjustment factor of 0.75 is used to allow for on-vehicle turbulence and

Table 7. Use factors for multiple-berth operations in linear stations.

	On-Line Stations[a]			Off-Line Stations		
Berth Number	Efficiency (percent)	Capacity Factor (cumulative)	Use Factor	Efficiency (percent)	Capacity Factor (cumulative)	Use Factor
1	100	1.00	1.000	100	1.00	1.000
2	75	1.75	0.875	85	1.85	0.925
3	50	2.25	0.750	75	2.60	0.867
4	25	2.50	0.625	65	3.25	0.812
5	–[b]	2.50	0.500	50	3.75	0.750

[a] Buses do not overtake each other. [b] Negligible.

Figure 2. Downtown busway line-haul service volumes.

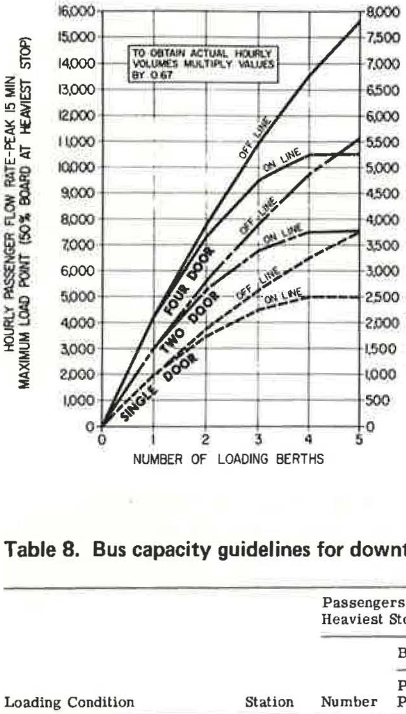


Table 8. Bus capacity guidelines for downtown busways.

		Passengers Boarding at Heaviest Stop			Berth Use (buses/hour)				Passengers/Hour at Heaviest Stop	
			Boarding Time (sec)							
Loading Condition	Station	Number	Per Passenger	Total[a]	Maximum per Berth	Use Factor (3 berths)	Total All Berths	Adjusted All Berths[b]	Peak[c]	Average[d]
Single-door conventional bus, simultaneous loading and unloading	On-line	25	2.0	65	55	2.25	124	93	4,650	3,115
	Off-line	25	2.0	65	55	2.60	143	107	5,350	3,570
Two-door conventional bus, both doors loading or double-stream doors simultaneously loading and unloading	On-line	25	1.2	45	80	2.25	180	135	6,750	4,520
	Off-line	25	1.2	45	80	2.60	208	156	7,800	5,200
Four-door conventional bus, all double-stream doors loading	On-line	25	0.7	32.5	111	2.25	250	188	9,400	6,300
	Off-line	25	0.7	32.5	111	2.60	289	217	10,850	7,230
Six-door articulated bus, all doors loading	On-line	30	0.5	30	120	2.25	270	200	12,000	8,040
	Off-line	30	0.5	30	120	2.60	312	234	14,040	9,360

[a] Includes 15-sec bus clearance.

[b] Adjusted by a factor of 0.75 to account for turbulence, schedule irregularity, and the like.

[c] From Figure 2.

[d] Adjusted by a factor of 0.67 to convert from peak.

schedule irregularity,

5. A peak-hour load factor of 0.67 is used to convert from peak 10- to 15-min flow rates to overall average hourly volumes, and
6. Fares are prepaid (no fares collected on bus in CBD).

Implications for Busway Planning

1. Busway capacity should be expressed in terms of persons per hour, rather than vehicles per hour. The governing factor will be the peak boarding and alighting volumes at the heaviest (downtown) stop.
2. The number of bus berths required at the maximum CBD stop largely depends on (a) the proportion of total busway passengers using the stop, which relates to system layout; (b) the boarding service times per passenger, which depend on operating patterns, door configurations, and bus seating capacities; and (c) the ability to develop off-line stations, which relates to facility design and level of investment.
3. Capacities provided by conventional urban buses can be more than doubled by separation of loading and unloading operations and use of buses with double-stream doors.
4. Articulated buses, with three sets of double doors available for passenger loading, can approximate capacities attained by single-unit streetcars (up to 140 cars/hour in the Philadelphia subway during concentrated loading conditions).
5. Off-line stations can increase capacity, especially where multiple berths are provided. This sometimes may be difficult or costly to achieve in a downtown environment, especially where underground construction is involved and building setback lines are limited.
6. Busway planning should try to provide at least three stops in the central area, and the maximum stop should not serve more than 50 percent of the total entering or leaving peak-hour passenger volume.

Research Directions

Additional information should be obtained on passenger interchange (simultaneous boarding and alighting) and its effect on passenger service times and the efficiency of the bus berth as a function of the number and configuration of berths. Some research has been done in these areas, but it should be expanded to reflect European experience with double-door vehicles.

ACKNOWLEDGMENTS

This paper draws on our experience in National Cooperative Highway Research Program Project 8-10, and Federal Highway Administration Project HGS 1-12, RFP-81. We also acknowledge the constructive assistance of Vukan Vuchic, University of Pennsylvania.

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DISCUSSION

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Capacity, being an important characteristic of transportation modes, has always received considerable attention in professional literature. Unfortunately, understanding of this rather complex concept has not been steadily progressing. Following the extremely valuable reports by Rainville et al. (15) and by the Institute of Traffic Engineers (16), there have been a number of studies, data collections, and computerized models based on inadequate experience with urban transportation modes. Often influenced by some promotional feelings, these studies produced highly erroneous figures and created considerable confusion. The paper by Hoey and Levinson represents a refreshing return to reality. It brings out several important relationships, although some of its analyses justify additional comments.

There are three basic facts that must be understood and correctly treated in capacity analysis.

1. Station capacity C_s and way capacity C_w are two different concepts. Capacity of a transit line C is equal to the smaller of the two:

$$C(\text{per hour}) = \text{Min}(C_s, C_w)$$

As Hoey and Levinson point out, station capacity is critical under nearly all conditions since the minimum headway between successive vehicles is much longer at stations than between moving vehicles. Increase in line capacity can be achieved only by reducing vehicle times at stations or increasing the number of stopping positions.

The critical station is the one that has the highest boarding and alighting passenger volumes per vehicle. That is not necessarily related to the maximum load section (the commonly used concept of the maximum load point is incorrect because the maximum load occurs on a section between stations rather than at a station).

Three major factors cause slow bus-boarding rates on most U.S. systems: single-channel doors, on-board fare collection, and low platform boarding. The first two can be corrected respectively by different vehicle design and application of modern fare systems (flash passes, honor fare collection, or ticket-selling machines at stops). Low platform boarding cannot be overcome; it is inherent in bus technology. Hoey and Levinson's suggestion that separation of alighting and boarding can significantly increase capacity is applicable only at terminal points; at stops along the lines, this type of operation is usually inadvisable since it would result in major delays and disturbances of service.

2. There is a great difference between theoretical computations or fully controlled tests of line capacity and actual capacities achievable by real, operating systems. Computed capacities are usually much higher particularly for systems without centralized control of vehicle travel. However, for systems, such as rapid transit, that have the highest degree of control, computations may show that frequencies of well over 40 trains/hour are possible; however, most systems can achieve only 36, 38, or, exceptionally, 40 trains/hour. This paper does not point out this important fact; some of the entries in Table 1 have no realistic validity and may cause confusion.

3. Capacity must be considered with service quality. Some literature mentions passenger comfort (seating versus standing) and running speed as service elements, but such important factors as safety and reliability are usually ignored. A system transporting 10,000 persons/hour at 9 mph (15 km/h) in vehicles so closely spaced that chain collisions are possible is drastically different from the system carrying the same passenger volume at 18 mph (30 km/h) on an automatically controlled, fail-safe system. Again, this paper does not put sufficient emphasis on these considerations.

Disregard of all these three facts has led to widespread quotations of much higher capacity figures than actual systems can ever achieve. Most common exaggerations have been found with respect to buses and personal rapid transit systems. One example of all three errors combined is the result of the General Motors Proving Ground test of buses running on freeways (Table 1). First, uninterrupted flow that was tested never determines capacity: Stops, terminals, or ramps are the bottlenecks. The closest case to reaching way capacity is the Lincoln Tunnel approach in New York City, in which the bus lane leads into a terminal with 184 berths, certainly a situation atypical for any transit line. Second, the conditions prevailing during the tests were artificial; they do not exist on any freeway. Third, an analysis of the quoted flow of 1,450 buses/hour (Table 1) at 33 mph (53 km/h) through application of basic equations of vehicle traction and dynamic behavior clearly shows that such a flow can occur only under conditions at which safety is well below the minimum safety required for any transit system. Thus, the capacity of 76,850 seated persons/hour for buses, similar to the quoted personal rapid transit capacities of ≥6,000 to 10,000 passengers/hour (capsules following each other at various fractions of a second!), is without any realistic or scientific value. These figures only lead to confusion.

The average hourly passenger volumes, ranging between 3,100 and 9,350, as reported in this paper, are realistic. However, under what conditions can the claimed 50 percent higher 15-min rate be achieved? Such conditions may not be common.

The attempt to develop equations is a step in the right direction, although the given equations can be somewhat improved. For example, passenger boarding and alighting volumes should be given as absolute numbers rather than percentages of vehicle capacity.

In conclusion, the paper presents some refreshing, realistic views; it contains useful data and raises important questions that, as the authors also point out, need considerable further study.

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AUTHORS' CLOSURE

We appreciate the pertinent discussion of Vuchic and Day. Many of their comments are reflected in this paper. For example, Table 1 only contained theoretical bus performance; Table 2 gave only observed (actual) data.

We agree with Vuchic and Day that way and station capacity are different concepts and that the smaller of the two determines system capacity. Their comment correctly highlights and clarifies this important fact. However, they believe that the maximum load-point volume and capacity remain useful concepts; every major transit property conducts maximum load-point checks to assist in route and schedule planning.

In regard to separation of alighting and boarding within stations, we foresee selective application, such as at major interchange stations where a large proportion of passengers transfer between routes. These stations would have the characteristics of a bus terminal, except that through passengers would not be forced to change buses to continue their journey. Such applications of separate boarding and alighting generally would be exceptions to the operating procedures suggested by Vuchic and Day.

We separated the theoretical computations of capacity from observed volumes because the former were not based on real-world experience. (The capacities of stations, car doors, junctions, and terminal train-reversing facilities usually limit rapid transit line capacity—just as station capacity usually limits bus systems.)

We consider 1,450 buses/lane/hour to be analogous to the lane capacity of 2,000 passenger cars/hour (2) for ideal conditions. In actuality, as Vuchic and Day point out, this theoretical lane volume is academic because either demand or station capacity is limiting. Most urban bus fleets operate at a substantially lower volume.

Service quality, particularly service reliability, is indeed implicit in bus capacity assumptions. The capacity analysis in the paper sought to establish the maximum number of people who can be accommodated without risking serious disruption of service. The paper recognized this in the following ways:

1. By using 15-min peak flows, rather than peak-hour totals, as a basis for investigation;
2. By reducing theoretical station volumes derived in the analysis by 25 percent; and
3. By recommending use of seating capacity only (rather than seating and standing room combined) in bus capacity calculation.

The ability of the system to accommodate 15-min peak loads at 1.5 times the hourly rate depends on such nonphysical factors as staggering of work hours within buildings, radio communication between bus drivers and dispatchers, and the ability of bus system management to compensate for perturbations in bus schedules that may result from breakdowns and other incidents.

Accordingly, the findings in this paper represent real-world conditions that can be applied in practice and that could complement the capacity charts, nomograms, and tabulations presented in the Highway Capacity Manual (2).

We agree that further research will be needed, particularly in regard to the impact of on-vehicle turbulence on dwell times. Although we discussed the effects of boarding and alighting on dwell times, the impact of simultaneous interchanging of large passenger volumes requires additional study. A third area to be explored is the effect of comfort and load factors on the attractiveness of bus service.

FRAMEWORK OF ROUTE SELECTION IN BUS NETWORK DESIGN

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The purpose of this study is to establish a framework of route selection in bus network design, based on the proposed functional description and evaluation system. In the proposed framework, the network is classified into residential, activity, and transfer nodes. Routes connecting the transfer nodes serve as the regional system, and other routes constitute the local systems. The evaluation system designed is capable of reflecting both the connectivity of transfer nodes and the accessibility of the residential and activity nodes. To establish the priority of route selection, several attributes were tested against transit use at the neighborhood level. The level of transit service was the sole dominant factor in the traveler's determination of mode choice. Furthermore, the employment activity nodes were significantly correlated with route performance. If the work trips and route performance are given prior consideration, employment serves as a good index during the process of network development. If the provision of accesses to other activities is taken into consideration, employment can also serve as a good indication by connecting those activity nodes to the other elements of the network. This framework will be especially useful when it is integrated in a heuristic algorithm for optimization of network design. A case study was carried out to demonstrate the use of this framework in four stages of bus network development in the Denver area.

•BUSES have long been recognized as the transit mode most suitable for serving cities of moderate size. The advantages of bus transit include the flexibility that enables management to make proper route changes when necessary. Ironically, the bus route configurations in most cities have remained almost unchanged since the bus was substituted for trolleys in the 1950s. Only in recent years has the importance of a large-scale reevaluation and change of bus routes been realized.

Many studies on network design have been carried out since then. Basically, there are two approaches to dealing with the network design: (a) the application of mixed-integer programming (1) and (b) the development of heuristic searches (2). Among these efforts, the integer programming approach is still not capable of dealing with networks of realistic size, and the heuristic approach has yet to obtain an acceptable optimization algorithm.

The computer programs capable of making long-range plans for the transit systems have been developed and applied to the daily planning practice (3). These programs, however, are designed primarily for simulating the networks, projecting the demands, and evaluating the level of service: in other words, for analyzing rather than for constructing networks. The problem of developing priorities remains unsolved.

This study attempts to provide planners with a framework for route selection in network design. The proposed framework includes a functional description of various elements of the network, a comprehensive evaluation system for the individual route and the entire network, and a priority algorithm for indicating development priority. It provides the planners a clear view of the network structure and allows them to develop and specify alternatives for network design. In particular, the framework helps planners to integrate routes of various functions into a network and to reach a balance between generating revenues and providing access.

Data were collected and analyzed at the district level (63 districts in the case study area in contrast to 120 census tracts in the same area). In the network, each district was represented by a residential node, and activity centers were identified and designated as activity nodes. Bus routes thus developed represent transit corridors rather than the exact locations of routes.

PROFILE OF TRANSIT USERS

A better understanding of the characteristics of transit users would help planners in network design. In the past, the trip-makers' socioeconomic backgrounds were believed to be the most important determinants for their modal choice behaviors. It is only in recent years that the importance of the system characteristics of transit modes in the modal choice decision has been realized (4). Among the socioeconomic characteristics, family income and automobile ownership are considered to be the most important factors, and the system characteristics are often represented by the level of service.

A survey conducted in 1970 in the Denver area (5) showed that 69.4 percent of transit users were female riders, and the 1970 census showed that only 51.35 percent of the general population of the city of Denver were female. The age profile showed that senior citizens (age over 65) accounted for 12 percent in transit users in contrast to 7.74 percent in the general population. Transit users also have generally lower incomes than the average Denver resident. Almost 42 percent of transit-user households had incomes between $3,000 and $6,000, and 21 percent had incomes of less than $3,000. In total, 81 percent of transit-user households had incomes less than $9,000. In comparison, half of the general households in the city of Denver had incomes less than $9,654.

Another survey conducted in 1970 (6) revealed similar results. In addition to providing the information on the rider's sex, age, and income, the San Diego survey showed that less than 57 percent of transit-rider households had an automobile in 1970 and that 78 percent of the general households had one in 1966. When asked if there was an automobile available for the trip being taken, 84.4 percent of the transit users replied negatively. From these results, it is obvious that the transit captives account for a rather high percentage of today's transit users. But it does not mean that socioeconomic characteristics are the dominant factors in the modal choice decision. As a matter of fact, the following study shows that level of service is the only significant factor in determining the percentage of transit users at the district level.

An index for the level of service was designed to reflect both the schedule frequency and transit routing:

$$S_i = \sum_{k=1}^{K} A_{ki} B_k \sum_{n=1}^{N} A_{kn} D_{in} \qquad (1)$$

where

S_i = index for the level of transit service of district i,
A_{ki} = percentage of area served by transit route k in district i,
B_k = frequency index for route k, and
D_{in} = number of trips originated in district i and terminated in destrict n.

In addition to the service index, four socioeconomic factors were chosen for the test of transit use. These four factors are percentage of (a) residents over 65 years old, (b) households with incomes below the fifteenth percentile, (c) households without an automobile, and (d) minority residents, including people with Spanish surnames, blacks, and other nonwhites. Origin-destination information and socioeconomic data for each district were obtained from the Denver Regional Council of Governments and the city and county of Denver; 25 districts were excluded from the test because of the lack of data or the lack of transit service.

Results of the correlation tests indicated that the service index was correlated to the transit use. The correlation coefficient between them was 0.758. In comparison, all of the four socioeconomic factors had much lower correlation coefficients with the transit use (Table 1).

To calculate the percentage of transit use for each district, three regression equations with one, two, and three independent variables respectively were used:

$$T_i = 0.805 + 0.021\ X_i \qquad (2)$$

$$T_i = 0.336 + 0.020\ X_i + 0.015\ Y_i \qquad (3)$$

$$T_i = -0.382 + 0.018\ X_i + 0.019\ Y_i + 0.068\ Z_i \qquad (4)$$

where

T_i = percentage of transit use in district i,
$X_i = S_i$ = index of transit service in district i,
Y_i = percentage of minority residents in district i, and
Z_i = percentage of senior citizens in district i.

The coefficients of determination R^2 for these three regression equations are 0.575, 0.632, and 0.656 respectively.

From the test, it is concluded that the level of transit service is far more important than the socioeconomic factors in determining transit use. This finding was confirmed by an attitudinal survey conducted in Denver (5, 7). It showed that, among those people not using public transit, 31.4 percent cited routing problems, and another 25.5 percent cited problems relating to bus scheduling.

DESCRIPTION OF NETWORK

The bus network is composed of two elements: nodes and links. Links are the segments of bus routes, and nodes represent the points where bus routes terminate or intersect. In the general procedure of network description, routes are identified first with nodes and then determined by the terminals and intersections of routes. For this study, however, an opposite approach is adopted. All potential nodes are identified first. Routes are then laid out to link nodes into a network.

Bus networks transport people from their residences to activity centers and among

Table 1. Correlation analysis.

Variable	Transit Use	Income Level	No Automobile	Minority Resident	Over 65 Years
Income level	0.3580				
No automobile	0.4787	0.9310			
Minority resident	0.2911	0.6942	0.5529		
Over 65 years	0.3829	0.1690	0.3305	-0.3115	
Transit service	0.7586	0.1886	0.3635	0.0705	0.4416

activity centers. Two types of nodes, activity and residential nodes, are considered separately in this study. Activity nodes are those areas where social or economic activities concentrate, and residential nodes are the centroids of residential areas. Some of the activity nodes are further designated as major transfer nodes, and this will be given special attention in this study.

Activity and Residential Nodes

Activity nodes can be further divided into two categories: employment nodes and nodes for shopping, social-recreational, health care, and cultural activities. According to transit surveys (6, 8), transit service has primarily been used for home-based work trips. If the bus service is designed specifically for this purpose, employment nodes should be given priority consideration in selecting activity nodes. However, a substantial percentage of households in American cities do not own an automobile (9). For these transit captives, public transit is the only alternative, other than walking, for trips of all purposes. When bus service is provided from this point of view, many activity nodes besides employment nodes have to be taken into consideration. For instance, to provide access to health care facilities, hospitals, especially those that are involved in social welfare programs and that cluster together to become major medical centers, should be designed as nodes. Other activity nodes in the network could include regional shopping centers, sports stadiums and coliseums, art museums and performing centers, zoos and parks, and other areas that are of regional importance.

The number of nodes should be kept relatively small so that the analysis will be easy to handle. If the number of nodes becomes too big, it might be desirable to group nodes into several categories and to assign a priority to each of them. Only those nodes in the category with the highest priority are considered in the early stages. Other nodes are taken into consideration subsequently when the network gradually develops.

When the activity nodes cluster to form a strip, it is called an activity corridor. Activity nodes are at one end, and bus routes lead through the residential areas and terminate either at another activity node or at a residential node. The division of the service area into residential zones is based on two considerations:

1. The size of zones should not be so large that each zone loses its identity and uniformity of socioeconomic characteristics, and
2. The number of residential zones should not be so large that the size of networks exceeds the capacity of the analytical tool.

Many existing divisions of zones can be used for network design. Among them, the census tract is one of the most familiar and available divisions. In cities where origin-destination surveys have been conducted, the traffic zone provides another division for use. Other divisions, such as neighborhoods and communities used in the neighborhood analysis, are also useful. In the case study area, there are 120 census tracts, 234 traffic zones, and 63 neighborhoods. Neighborhoods were used as the unit for residential zones in this report. The centroids of residential zones represent only the existence of zones and do not provide accurate locations for buses to pass by. Consequently, the locations of centroids are relatively unimportant and are considered variable during the analysis.

Major Transfer Nodes

The major transfer node plays a dual role in network design. As a bus center, it is the terminus and intersection of bus routes that serve the surrounding neighborhoods and local activity nodes; as a transfer point, it provides the local residents easy access to other subregions in the metropolitan area. These transfer nodes should be located in the area of major traffic attraction and should have easy access both to local neighborhoods and to other transfer nodes. In recent years, the development of intense activity centers, which provide many diverse activities for the local communities, has attracted much attention. These intense activity centers are, of course, ideal locations for transfer nodes. Other transfer nodes could be located in local employment centers or major shopping centers. The design for these transfer nodes should be stressed to provide easy transfer facilities and comfortable waiting spaces.

Another consideration in selecting major transfer nodes involves the geographical relationship among all transfer nodes of the entire network. Ideally, these transfer nodes should be scattered around the service area to provide the optimum accessibility for the entire area. In practice, however, the specific urban form for each service area turns out to be the predominant factor in arranging the transfer nodes.

Classification of Bus Routes

Bus routes are conventionally classified into radial routes, crosstown routes, and feeder lines according to their geographical relationship with the central business district. For network design, however, this classification has not been found appropriate for several reasons. First, the traditional classification envisions the CBD as the only node of regional importance and does not distinguish other activity nodes from the residential nodes. As a matter of fact, the solely dominant role of the CBD in the urban structure has been substantially reduced because of suburbanization and decentralization of business industry in the past two decades. Therefore, it would be more realistic to treat the CBD as one of the activity nodes and make a distinction between activity nodes and residential nodes. Second, the traditional classification does not reflect the different functions that various types of bus routes provide. Urban street systems have long been classified according to their respective functions; bus routes have not. To provide satisfactory service to the public and to revive the declining transit industry, the same concept of functional classification should be applied to the bus network design.

We propose that bus routes be classified into the following categories according to the nature of nodes along the routes:

1. Bus routes that connect two major transfer nodes,
2. Routes that serve an activity corridor,
3. Routes that connect two activity nodes, and
4. Routes that extend from one activity node into the residential areas.

The routes in the first category form a framework for the regional system, and those in the other three categories constitute local networks.

EVALUATION OF NETWORK

The criteria for a good network are difficult to define. For instance, Lampkin and Saalmans (2) and Wren (10) state that a good transportation network should not have too many routes, require too many transfers, and meander excessively. Stating the criteria as such, however, is impractical unless a quantifiable measure for them can be defined and easily adopted into the objective function. According to Miller (11), the assessment process for the transportation system should include

1. Establishing the major objectives that are to be optimized,
2. Listing all performance attributes that are relevant to the objectives, and
3. Selecting a physical performance measure for each attribute.

In the following sections, objectives and performance attributes for bus service are discussed, and measurements for the bus network are proposed.

Characteristics of Bus Network

An intraurban bus network can be distinguished from other transportation networks in many aspects. The flexibility of the bus operation makes it different from a guideway transportation system; almost all streets that are physically suitable for bus operation can be developed as bus routes. However, except for a few newly innovated concepts of bus operation, such as dial-a-bus, buses are operated on the basis of fixed routes and fixed schedules. When the direct route connection is not available, the unavoidable transfer and waiting would reduce bus use substantially. The number of transfers should, therefore, be watched closely during the process of network design.

For those people who have an automobile of their own, buses are considered as an alternative. Because of this competitive nature between buses and automobiles, the relative advantages of each mode should be able to be revealed from the network measurements. And because a majority of bus companies in American cities have been purchased by the local authorities and subsidized by the public in recent years, a fair and uniform coverage of bus service among all neighborhoods is often required by the local authorities. A good measurement of the network should, therefore, reflect the coverage of service and the discrepancies of the coverage.

Among the guidelines proposed in 1958 by the National Committee on Urban Transportation (12) for measuring the transit service, some, such as the directness and density of routes, were particularly relevant to network design. Since then, more measures have been proposed based on various objectives. The area of coverage, number of transfers, and degree of accessibility are among the measures that are often used in the objective function for optimizing network design. For this study, an objective function including operating revenue, accessibility for residential nodes, and connectivity for transfer nodes is used during network development. Operating revenue is directly affected by the ridership and can be easily measured by the number of passengers per bus mile (kilometer). The measures for the accessibility and connectivity, however, are much more complex. Accessibility has been interpreted quite diversely among transportation planners, and many different measures have been proposed (13). However, connectivity, a concept that originated from the graph theory and that is widely used by the geographer, is rather unfamiliar to many planners. In this study, both accessibility and connectivity will be defined from the geographical point of view. Some modifications are made to meet the requirements that emerged from the previous discussions.

Network Measurements in Graph Theory

Graph theory has long been used by transportation geographers to describe the structure of networks. The aggregate geometrical patterns of the network are measured by indexes with a single number; the relations between elements are measured by matrices. The aggregate indexes are most meaningful for comparing two networks or for describing the various stages of network development (14). Werner et al. (15) reported that these indexes failed to discriminate the networks that have the same numbers of nodes and links but significantly different structures. However, the measurement matrices, which are capable of pinpointing the weaknesses of networks, are most useful in the person-machine interactive type of network design. Three of these matrices used in this study are described below.

C is the connection matrix, where element c_{ij} indicates the connectivity between nodes i and j. $c_{ij} = 1$ shows that nodes i and j are directly connected; $c_{ij} = 0$ indicates the absence of connection. C can be multiplied by itself to produce a new matrix C^2, where element c^2_{ij} indicates the existence of the two-linkage path between nodes i and j. A further generalization of this concept indicates that the n-linkage paths between nodes can be represented by C^n. The accessibility matrix T is then defined as the sum of C and its powers:

$$T = C + C^2 + C^3 + \ldots + C^n \tag{5}$$

where n is the network diameter that is defined as the minimum number of linkages required to connect the two nodes that are the greatest distance apart on the network. T has been used to describe various transportation networks; e.g., Garrison (16) used it to study the Interstate Highway System in the southeastern United States.

The elements of the shortest path matrix D indicate the number of linkages of the shortest path between all pairs of nodes in a network. D can be generated by successively powering C. Originally, all cells in the matrix without the direct connection are recorded as 0. Other cells are recorded as 1. If any new non-0 element occurs after each iteration of powering, the power of that iteration is entered into the corresponding cell in D. D is completed after all 0 elements, except those in the main diagonal, are eliminated.

The major concern of the graph theory is the presence or absence of links between nodes. Sometimes, however, it takes into consideration the characteristics of individual routes. When this is the case, networks are treated as the valued graphs. Instead of the number of linkages, the actual measurement of route characteristics appears in cells of the matrices. Under some systematic procedures, matrices of the valued graphs can be powered to produce the information needed.

C, T, and D matrices are useful when the transfers are of concern; however, the matrices of valued graphs provide information when travel time, either absolute travel time or the relative time to the automobile, is under consideration.

Proposed Measures of Network Design

The proposed measures for the network design include

1. The gamma index, the ratio of the actual number of links to the maximum possible number of links in the network, and the connection matrix for measuring the connectivity of transfer nodes; and
2. T, D, and a relative traveling distance matrix R for measuring the accessibility of residential and activity nodes.

The element r_{ij} in R is the ratio of the distance traveled by bus to that traveled by automobile from district i to j.

ANALYSIS OF PRIORITY FOR ROUTE SELECTION

The performance of routes is tested against attributes associated with the nodes along each route. Precedent analysis of transit use at the district level indicated that the level of transit service was the solely dominant factor in determining the percentage of transit uses. Socioeconomic factors turned out to have little effect on transit use. Based on this finding, it was suggested that the data on trip generation and trip distribution alone could provide enough information for network design at the district level. In this study, the employment numbers at the activity nodes along each route were tested as the primary index for establishing the priority for route selection.

Methods

Because the number of routes is relatively small, nonparametric methods were used in the analysis. The Wilcoxon rank sum test (17) was used to distinguish the performance differences between two types of routes, and the Kendall rank correlation test was used to test the correlation between two attributes.

Data used for the analysis were obtained from a passenger census (18) conducted in

1973 by the Denver Metro Transit (DMT). At the time of survey, there were 26 regular routes, served by DMT, which could be further broken down into 37 links. Information on total passengers, total bus trips, average passengers per trip, route miles (kilometers), and passengers per mile (kilometer) are compiled for each route. Based on this information, an overall rating is then calculated according to the following equation (19):

$$R_i = \frac{100}{2} \times \left(\frac{P_i}{\sum_n P_n} \times \frac{\sum_n Q_n}{Q_i} + \frac{P_i}{\sum_n P_n} \times \frac{\sum_n M_n}{M_i} \right) \tag{6}$$

where

R_i = overall rating for link i,
P_i = number of passengers for link i,
Q_i = number of trips for link i, and
M_i = route miles (kilometers) for link i.

The number of passengers per mile (kilometer) is another index that has been used often in measuring the route performance. Ranks of links according to these two indexes were then used for the Wilcoxon and Kendall tests.

Distinctions Among Various Types of Bus Links

Among the 37 regular links, only 9 of them were not connected to the Denver CBD. Excluding the route that served only the downtown area and the Mile-High Shuttle, which connected the CBD to parking lots around the Mile-High Stadium, there were 26 radial links. The Wilcoxon rank sum test (Table 2) shows that for the overall rating there is a significant difference between radial and crosstown links. (In Tables 2 through 6, M and N are the sample sizes of the two categories tested; T, T_1, and T_2 are the sums of the ranks of the category with the smaller sample size; and T_u and T_e are the critical values for T, T_1, and T_2 when the level of significance is p.) Measures of the passengers per mile (kilometer) are also significantly different for the two types of links (Table 3). The results are not surprising because the Denver CBD still is the most important employment center in the Denver metropolitan area. Moreover, because the Denver CBD has been the only major transfer point in the existing bus network, many people ride buses to downtown just to transfer to the other buses.

What is more interesting in this study is the difference between the links that connect two employment centers and the links that extend from employment centers to residential areas. In the case of DMT, among the 28 radial links that have the CBD at one end, 9 have another employment center at the other end of the link, and the remaining 19 links are extended to residential areas. The rank sum tests (Table 4) suggest that there are significant differences between these two types of links. For the 9 crosstown links that do not connect with the CBD, the difference also exists as given in Table 5.

Among the DMT links, link 3 is the only one that is qualified as the corridor route according to the previous definition. This link has the highest overall rating score but the second highest number of passengers per mile (kilometer).

The passenger profiles, which show the number of passengers on board during the morning peak hours along the routes, indicated more differences among the various types of bus routes. Figure 1a shows the profile of a route extending from the CBD to the residential areas in northeastern Denver. The dotted curve indicates that the outbound buses are almost empty. Figure 1b shows the route that goes from the CBD along the Broadway Street corridor. The profile shows that the numbers of passengers getting on and off the buses are quite uniformly distributed along the route for both the outbound

Table 2. Wilcoxon rank sum test for overall ratings.

Crosstown			Radial		
Link	Score	Rank	Link	Score	Rank
9	103	16	3	168.5	1
15	93	17	4E	129	7
17	37	30	4W	81	25
18	15.5	34	5E	133	6
19	106.5	4	5W	77.5	27
20	34.5	31.5	6E	110	12
55	34.5	31.5	6W	90	19
73	88	21	8E	135.5	5
80	8	35	8W	89.5	20
Total		220.0	13E	150.5	4
			13W	105	15
			14	167	2
			23	21	33
			28W	79.5	26
			40	119	11
			50E	87.5	22
			50W	127	9
			60S	119.5	10
			60N	41.5	29
			64E	160.5	3
			64W	110	12.5
			75E	71	28
			75W	83.5	24
			75Y	90	18
			84	84	23
			28E	128.5	8

Note: $M = 9$, $N = 26$, $T_u = 214$, $T_e = 110$, $p = 0.05$, $T = 220$, $T > T_u$.

Table 3. Wilcoxon rank sum test for passengers per mile.

Crosstown			Radial		
Link	Passengers/ Mile	Rank	Link	Passengers/ Mile	Rank
9	2.45	24	3	4.73	2
15	2.36	26	4E	2.75	21
17	1.14	31	4W	3.15	15.5
18	0.44	34	5E	3.68	8
19	2.93	18	5W	2.53	22
20	0.73	33	6E	3.28	12
55	1.15	30	6W	2.87	19
73	2.20	28	8E	3.33	11
80	0.19	35	8W	3.17	13.5
Total		259	13E	4.60	3
			13W	3.66	9
			14	4.12	6
			23	0.80	32
			28W	2.44	25
			40	3.17	13.5
			50E	3.52	10
			50W	3.71	7
			60S	3.05	17
			60N	1.26	29
			64E	4.75	1
			64W	4.23	4
			75E	2.77	20
			75W	2.49	23
			75Y	3.15	15.5
			84	2.22	27
			28E	4.19	5

Note: $M = 9$, $N = 26$, $T_u = 95$, $T_e = 259$, $p = 0.01$, $T = 259$, $T = T_e$. 1 mile = 1.6 km.

Table 4. Wilcoxon rank sum test for radial links connecting CBD and employment centers.

	Overall Rating		Passengers/Mile	
Link	Score	Rank	Number	Rank
64E	160.5	3	4.75	1
13E	150.5	4	4.60	3
5E	133	6	3.68	8
50E	87.5	19	3.52	10
8E	135.5	5	3.33	11
6E	110	12.5	3.28	12
3	168.5	1	4.73	2
64W	110	12.5	4.23	4
14	167	2	4.12	6

Note: $M = 9$, $N = 19$, $T_u = 182$, $T_e = 79$, $p = 0.01$, $T_1 = 65 < T_e$, $T_2 = 57 < T_e$. 1 mile = 1.6 km.

Table 5. Wilcoxon rank sum test for crosstown links.

Employment to Employment					Employment to Residential				
	Overall Rating		Passengers/Mile			Overall Rating		Passengers/Mile	
Link	Score	Rank	Number	Rank	Link	Score	Rank	Number	Rank
9	103	2	2.45	2	17	37	5	1.14	6
15	93	3	2.36	3	18	15.5	8	0.44	8
19	106.5	1	2.93	1	20	34.5	6.5	0.73	7
Total		6		6	55	34.5	6.5	1.15	5
					73	88	4	2.20	4
					80	8	9	0.19	9

Note: $M = 3$, $N = 6$, $T_u = 24$, $T_e = 6$, $p = 0.02$, $T_1 = 6 = T_2 = 6 = T_e$. 1 mile = 1.6 km.

Figure 1. Passengers on board for three types of bus routes.

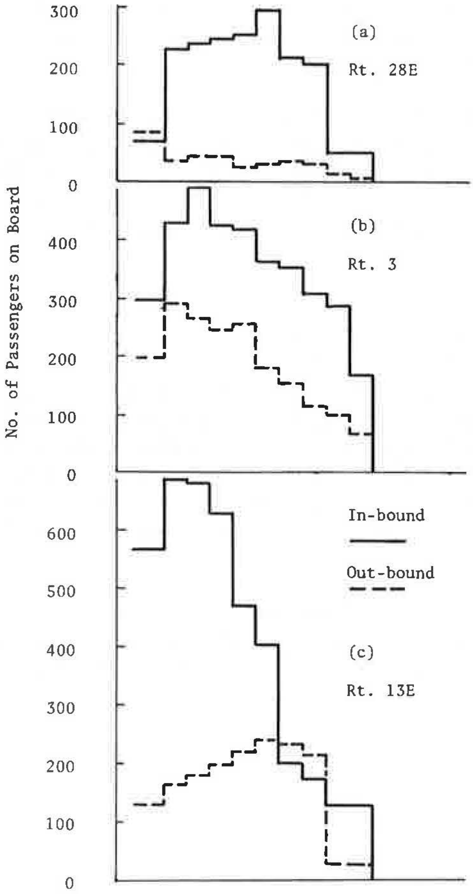

Table 6. Kendall rank correlation test.

	Passengers/Mile		Overall Rating		Employment	
Link	Number	Rank	Score	Rank	Number	Rank
64E	4.75	1	160.5	1	82,582	1
13E	4.60	2	150.5	2	78,887	2
5E	3.68	3	133	4	75,685	3
50E	3.52	4	87.5	7	72,342	5
8E	3.33	5	135.5	3	74,017	4
9	2.45	6	103	5	13,152	7
15	2.36	7	93	6	16,836	6

Note: 1 mile = 1.6 km.

and inbound trips. Figure 1c shows the profile of the route that serves between the Denver CBD and the University of Colorado Medical Center area, which is the third largest employment center in the metropolitan area. The number of passengers on outbound trips, although not so impressive as the number on inbound trips, is still rather high.

Employment as Priority Index

Intuitively, the bus route will have a better performance score if it has larger employment centers at both ends of the route. The results of the Kendall rank correlation test verify this assumption. For those routes that connected two activity nodes, the total employment numbers of the employment nodes were summed and used as the test index. In Table 6, three ranks were assigned to each link according to the overall ratings, the number of passengers per mile (kilometer), and the employment numbers. Griffin's (20) graphical method was used to carry out the Kendall test, as given in Table 7.

The overall ratings and employment number are significantly correlated at the 5 percent level. The correlation between employment number and passengers per mile (kilometer) is even better; $p = 0.01$. The test results suggest that the number of employment centers along the route is a good indicator for the priority index in the network design. However, no similar relations were found for the routes that extend into residential areas.

Regional System and Accessibility of Network

The form of a transportation system significantly affects the levels of accessibility throughout the metropolitan area. The level of accessibility in turn stimulates the community growth and helps shape the urban form. If the desirable urban form in American cities is to strengthen and revitalize the CBD and to develop the intensive activity centers in the outlying parts of the metropolitan area (21), a regional transit system that provides easy accessibility to the CBD and to activity centers should be developed with great care. In the context of this study, this regional system can be formed by connecting major transfer nodes.

In conclusion, bus routes should be classified into four categories: routes connecting transfer nodes, routes serving the activity corridor, routes connecting the activity centers, and routes extending from the activity centers to residential areas. Development priority should be in this order.

CASE STUDY

Study Area

The study area (Figure 2) is roughly bounded by I-225 to the east, I-70 to the north, I-25 and Santa Fe Drive to the west, and Colo-88 to the south. It covers approximately two-thirds of the city and county of Denver, most of the cities of Aurora and Englewood, and all of Cherry Hill Village. The Denver CBD is located at the northwestern corner of the study area. Also included in the area are most of the important employment centers in the Denver metropolitan area. In 1970, the total population in the area was 435,544, and the employment number was 283,685.

Major Transit Nodes

The internal origin-destination data (Figure 2) revealed that the Denver CBD, Cherry

Table 7. Griffin's graphical method.

Treatment	Item						
	Rank						
1 (passengers/mile)	1	2	3	5	4	7	6
Control (employment)	1	2	3	4	5	6	7
2 (overall ratings)	1	2	4	3	7	6	5
	Intersection			k	n	e	d
1	2			4	7	21	1
2	4			8	7	21	1

Note: 1 mile = 1.6 km.

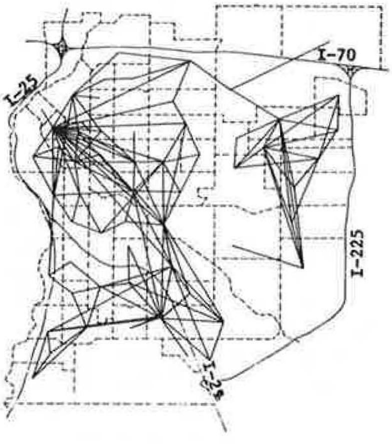

Figure 2. Study area and internal origin-destination data.

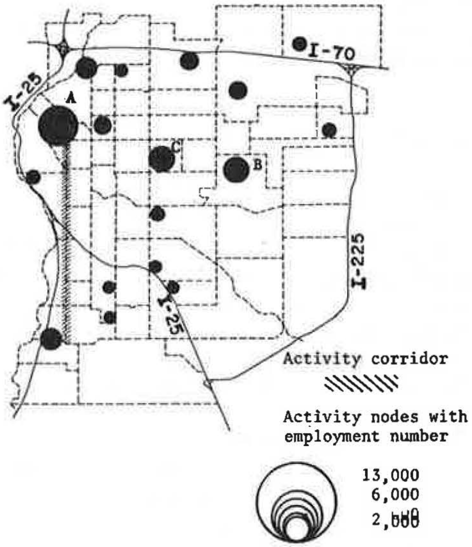

Figure 3. Residential districts, activity centers, and corridor in study area.

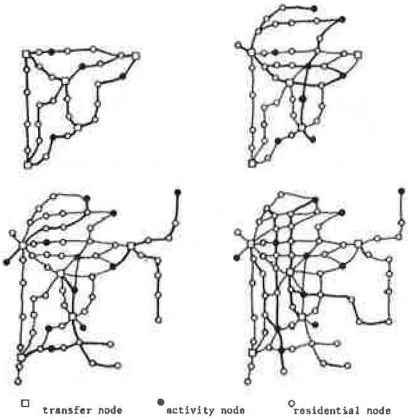

Figure 4. Network development in case study.

Creek, Englewood, South Colorado Boulevard, and Aurora were the five local traffic focuses. In addition to four of these five areas with the exclusion of the old Aurora CBD, the Denver Regional Council of Governments designated three more areas, including the newly proposed Aurora Community Center, as the intense activity center for future development. For simplicity, five existing traffic focuses as indicated by the origin-destination data were designated as transfer nodes.

Activity Nodes and Residential Nodes

In this case study, the total employment number per traffic zone was used as the criteria for designating activity nodes. In the study area, there were 63 zones that had an employment number of 2,000 or more. The adjacent zones were combined into 22 employment centers and one employment corridor (Figure 3). The largest 3 among these 22 centers were the Denver CBD, Lowry Air Force Base, and the University of Colorado Medical Center (A, B, and C respectively in Figure 3). The corridor was located along Broadway, extending from the Denver CBD south to Englewood. Among the 22 employment nodes, 3 were health care centers, and 1 was the airport.

For the residential nodes, the study area was divided into 63 districts or neighborhoods; each of them was represented by a residential node. The boundaries of these neighborhoods are also shown in Figure 3.

Network Development

The case study is restricted to the consideration of providing service for the work trips. The employment numbers of activity nodes were used as the priority index for the route selection. The first stage of the network development is primarily concerned with the regional system. Figure 4 shows that, if five routes are designated, each of five transfer nodes could have direct bus connections to the other four transfer nodes. This fact was reflected by a gamma index of 1.0 and a connectivity of the identity matrix I. Coincidentally, one of these five routes also served the only corridor in the study area.

The next stage involved the selection of the routes to connect activity nodes. Five of these routes were selected on the basis of employment numbers. The resulting accessibility matrix showed that 22 neighborhoods in the area had no bus service available. The number of districts without bus service was decreased to three by adding five routes in the next stage. All five routes could be specified as residential routes. In the last stage, when four more routes were added, all neighborhoods were served at least by one bus route. The last stage, however, was for the improvement of neighborhood accessibility rather than for the provision of uniform coverage. These four stages of development are also shown in Figure 4.

CONCLUSION

The framework is intended as a macrolevel model to help planners in determining transit corridors in network design. As such, it provides planners with an easy tool to specify and design preliminary alternatives on a rational basis.

One of the objectives of the study is to test the hypothesis of using the employment numbers of activity centers as the priority index in the network development. A functional description of the network structure and a comprehensive evaluation system were first developed. The functional description was designed to clarify the network structure and to integrate routes of various functions into a single system. The evaluation system was developed to help the planners reach a balance among various objectives of development.

Based on the new description and evaluation system, the planners can thus develop networks according to their own strategies in either providing service for work trips only or providing service for trips of all purposes.

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