most significant impact is a reduction of one in the number of buses and drivers required during weekdays. As a result annual operating costs are less, and the deficit is reduced to $76 479 compared to the base-case value of $84 756. There is also further improvement in the driver and vehicle utilization indicators and in the operating cost efficiencies, except for the cost per vehicle mile.

The main effect of simultaneous reductions in fare and spacing between stops in option 3 is to increase ridership relative to option 2. Operating costs remain the same due to no change in the number of buses; however, revenues decrease due to the reduction in fare. As a result, total deficit increases relative to option 2, but remains less than the base-case value. Option 3 is the most effective in terms of passengers per vehicle mile, passengers per vehicle hour, passengers per dollar of operating cost, and passenger miles per seat mile. Values of 19.458 passengers/driver-h and 73 675 passengers/vehicle are also the highest under this option.

In general, all three options offer significant improvements in most of the performance indicators. If a choice were to be made, it would have to be done with due regard to the relative importance of each performance measure and the magnitude of the trade-offs available.

CONCLUSION

A relatively simple and quick technique for analysis and assessment of the impacts of major operational policy variables has been presented in this paper. The technique involves identification of the impacts and use of simple mathematical relationships to measure them; particular emphasis is on performance. The applicability of the technique has been successfully demonstrated by a theoretical analysis of options for transit service improvement in a specific route of a case-study area.

The technique does not require an extensive amount of data collection effort; most of the information required is generally available from the records of a transit company. However, before it is applied, all of the assumptions made in the procedure must be considered and modified to suit a specific situation.

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Evaluation of Bus and Carpool Operations on the San Bernardino Freeway Express Busway

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The San Bernardino Freeway Express Busway, which runs eastward from downtown Los Angeles, is the most complete busway in the nation. It includes park-and-ride and on-line stations, feeder bus lines, outlying park-and-pool lots, and a supplemental contraflow bus lane in the central business district. Beginning in October 1976, carpools of three or more were permitted on this previously bus-only facility. During the mixed-mode operations, the number of carpools on the busway and freeway more than doubled, increasing by at least 800. These carpools were new and not caused by diversion from parallel roadways. Bus ridership was not noticeably affected until after a major fare increase. During the peak 1 h, the busway lane carries twice the number of people as does one adjacent freeway lane, but traffic still moves at 88 km/h (55 mph). Surveys were conducted among bus riders, busway carpoolers, and freeway users (busway nonusers). Most carpoolers said they would not be carpooling if they could not use the busway. Attitudes of most busway nonusers were positive; the busway is not controversial. There were no major safety or enforcement problems. The type of separation between busway and freeway was found to strongly affect safety and enforcement require-

ments. The busway was generally found to be more cost effective than an additional freeway lane. The average savings in out-of-pocket costs, for busway-induced carpoolers and bus riders only, covered two-thirds of the annual (capital and operating) costs of the busway. Most of these conclusions would probably change, however, if congestion on the adjacent freeway was reduced or eliminated (for example, because of ramp metering or freeway widening).

The San Bernardino Freeway Express Busway is a 17.6-km (11-mile) exclusive roadway for high-occupancy vehicles (HOVs), which runs eastward from the Los Angeles central business district (CBD) (see Figure 1). The two unidirectional busway lanes are built in the median strip or alongside the freeway and are separated from the automobile traffic lanes by either concrete barriers or a buffer lane that has flexible posts. This $57-million facility is the most complete busway in the country, with its on-line stations, park-and-ride facilities, feeder bus lines, outlying park-and-pool lots, and a supplemental contraflow bus lane in the CBD.

From October 1976 through June 1978, carpools of three or more were permitted on this previously bus-only facility from 6:00 to 10:00 a.m. and 3:00 to 7:00 p.m. This mixed-mode phase was done in two stages; carpools were permitted on only the eastern portion of the busway during stage 1 and on the whole length of the busway during stage 2.

This paper summarizes an evaluation of the mixed-mode phase (1). A brief summary of previous (bus-only phase) findings is also included for background.

SUMMARY OF PREVIOUS FINDINGS

During bus-only operations bus ridership grew steadily during the first 29 months of operation, from 1000 to 14 500 daily passenger trips (2). The number of riders then stabilized until October 1976, when mixed-mode operations were added (see Figure 2). During bus-only operations, 50 percent of the bus riders formerly drove alone and 25 percent came from a carpool (3). Only 11 percent of those riders were transit captives; the remaining 89 percent had an automobile available to them (3). New riders added during that time had substantially higher incomes than prebusway riders (3). The transit market share in this corridor has stabilized near 25 percent (of those trips whose origin and destination are both served by a busway bus) (2). This mode share is comparable to that of other forms of rapid transit. The principal reasons cited for choosing to ride a busway bus were time and cost savings and freedom from traffic congestion (2).

CORRIDOR IMPACTS

In the half decade that the busway has been in operation, travel demand in the corridor has increased substantially. This has been caused by population growth in the eastern end of the corridor and also by latent demand becoming manifest as new capacity was added. Thus, although busway usage has increased dramatically, the freeway lanes are used at or near capacity for about 3 h out of each 4-h morning and evening period.

During mixed-mode operations, the number of carpools on the busway part of the freeway has more than doubled, causing an increase of at least 800 carpools. These carpools were newly formed and not created by diversion from parallel roadways. During this period vehicle and person volumes on other major east-west roadways in the corridor have increased slightly, speeds have decreased slightly, and accident rates have increased slightly. The main cause of these changes appears to be population growth, but since the busway does not extend the full length of the corridor, growth has just increased the preexisting congestion at both of its ends.

FACILITY USAGE

Carpool volumes showed a slow, steady growth (similar to the prior growth in bus patronage) from about 600 to over 1400 automobiles in each 4-h morning and evening period (see Figure 3). At the observed occupancy of 3.3 persons/carpool, this translates to about 4600 carpoolers daily. Reverse-direction carpool volumes on the busway are negligible because the adjacent freeway is normally uncongested. Carpool growth is still continuing.

Bus ridership was not noticeably affected by the introduction of carpools. After the major fare increase in July 1977, perhaps 1000 bus riders switched from buses to carpools and single-occupant automobiles. However, by the end of the evaluation period bus ridership appeared to have regained its previous levels. During each 4-h morning and evening period the busway carries about 1600 vehicles, which contain about 10 000 persons. Half of these people are in carpools and the other half are in buses.

Total person volume over each 4-h period now slightly exceeds the average volume on one adjacent freeway lane. Demand on the freeway lanes is at capacity for most of the 4-h period, but the busway shows a sharp 1-h peak, which may be an expression of desired commute times versus the capacity-constrained commute times on the freeway. During this 1-h peak, the busway carries about twice the person volume of one freeway lane. Even at this volume, the busway is operating at only two-thirds of the estimated 88-km/h (55-mph) capacity of 1200 vehicles/h.

OPERATIONAL PERFORMANCE

Bus running times have not been noticeably affected by the introduction of carpools and remain about 14 min for the 17.6-km (11-mile) length (including two station stops). Carpool travel time on the busway is 12 min at all times. Automobile travel times on the adjacent freeway lanes have actually grown worse during mixed-mode operations because of congestion caused by merges at the ends of the busway, increased demand, and construction on parallel surface streets.

Thus, busway carpoolers can save up to 18 min in the morning peak and up to 8 min in the evening peak periods. This time savings can be even greater during incidents on the freeway lanes. The reliability of busway travel times gives further, unquantified savings to busway commuters because they do not have to depart earlier to be sure of an on-time arrival at work. An additional time savings may result from the flexibility to travel at any desired time.

MODE SHIFTS

More than half of the busway carpoolers surveyed said that they would not carpool if the busway had not been opened to carpools. This means that 2600 people now carpool as a direct result of mixed-mode busway operations. More than one-third of the busway carpoolers formerly drove alone, one-fourth came from buses, and a smaller percentage came from another carpool. Two-thirds of all carpool partners are coworkers. The turnover rate among carpoolers is estimated to be about 25 percent/year.

Figure 1. San Bernardino Freeway Express Busway.

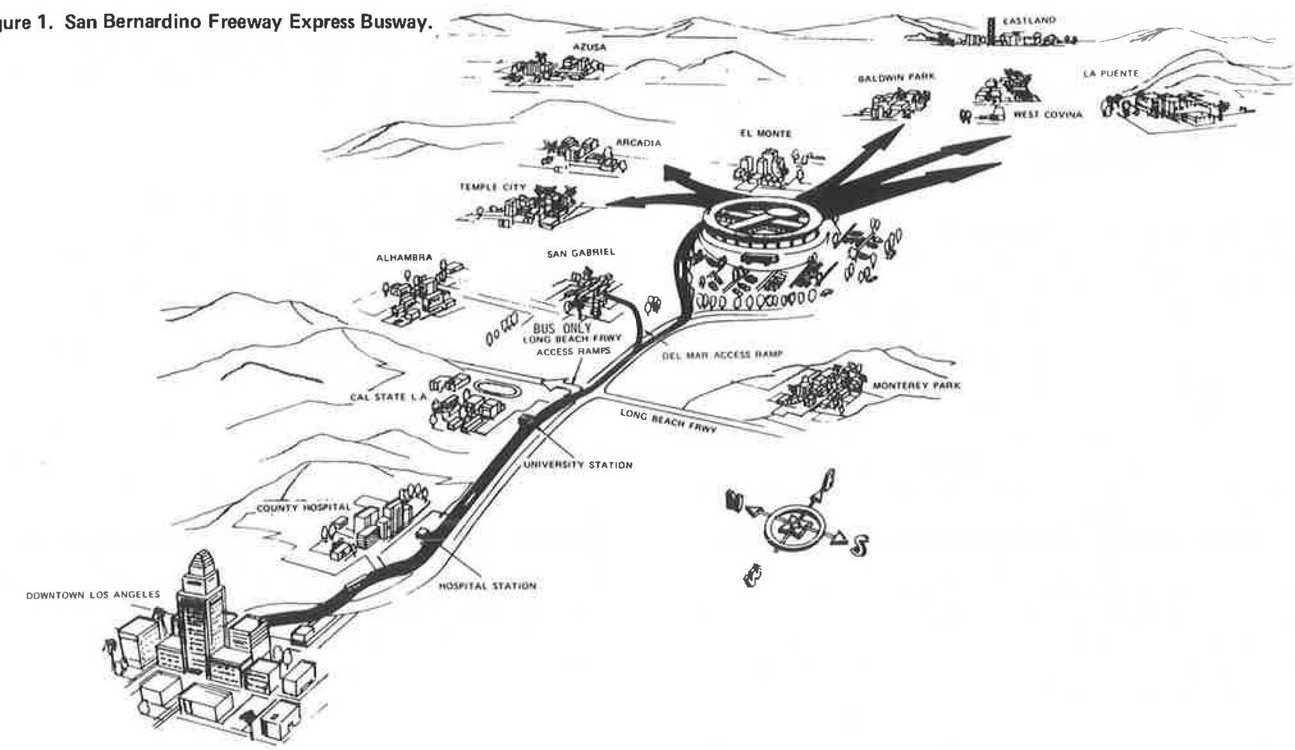


Figure 2. Busway patronage trends.

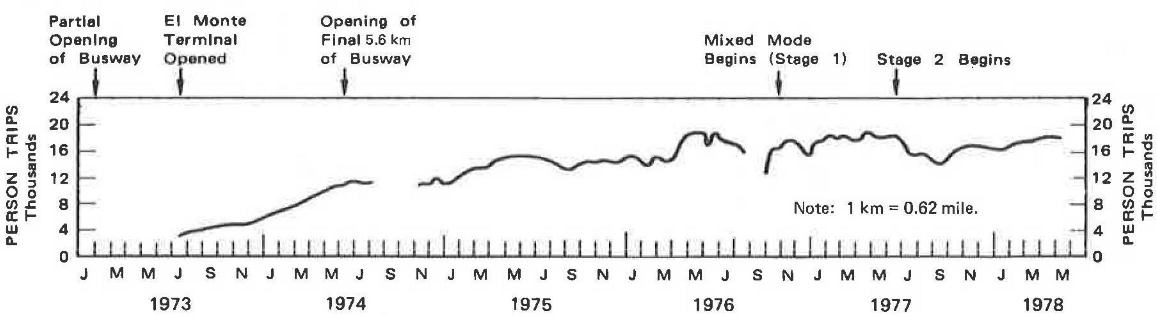
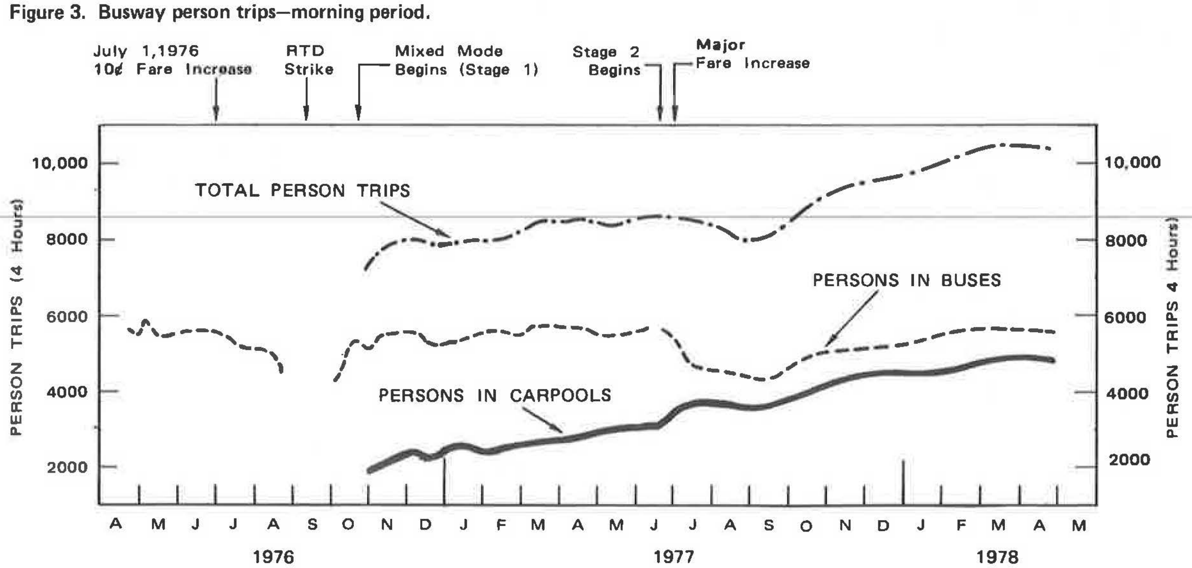


Figure 3. Busway person trips—morning period.



More than half of the carpoolers cited cost-related reasons for carpooling; time savings or convenience reasons were cited next most frequently. Parking costs are similar among carpoolers and solo automobile drivers. The major reasons cited by solo drivers for not carpooling were irregular work hours, the need for an automobile during the day, and convenience. Solo drivers' reasons for not riding a bus were time savings, convenience, and the need for an automobile. Carpoolers' perceptions of the time savings and pleasantness of carpooling were much more positive than those of solo drivers, but perceptions of carpool cost savings were similar. Most carpoolers agreed that they enjoy riding with other people; the solo drivers were neutral about that statement.

The large increase in bus fare in July 1977 caused roughly 200 bus riders to switch to carpools, but a greater number appear to have switched to a single-occupant vehicle. This is consistent with the findings about their prior mode of travel and automobile availability.

Figure 4. Western segment of busway.

Figure 5. Eastern segment of busway.

Figure 6. Access lane to busway.

ENVIRONMENTAL EFFECTS

The reduction in vehicle kilometers traveled just from those trips attracted to the busway during the 4-h morning and evening periods was 160 000 km/day (100 000 miles/day) during bus-only operations and 240 000 km/day (150 000 miles/day) during mixed-mode operations. The resulting reduction in air pollution emissions ranged from 10 to 20 percent and the energy savings from 7 to 10 percent of the 4-h, peak-direction totals on the busway-freeway lanes.

Although these savings were realized as a result of a major shift to HOVs, vehicular volumes on the freeway have also increased. This increased demand has offset some or all of the above savings. Other environmental impacts were inconsequential.

SAFETY AND ENFORCEMENT

The western segment of the busway is a physically separate roadway, accessible only at the end points (see Figure 4). The eastern segment of the busway is in the median of the freeway and is separated by a buffer shoulder with flexible posts (see Figure 5). Thus, it is possible to enter the busway at any point along the eastern segment, but it is illegal to do so except at the legal access points at the ends. Further, there are two lengthy access lanes to and from the busway where HOVs are separated from the freeway lanes by nothing more than a stripe on the pavement (see Figure 6). These differing configurations have a pronounced effect on safety and enforcement.

During bus-only operations, there were virtually no accidents, violations, or enforcement problems on any of the three parts of the busway. During mixed-mode operations, the same thing held true on the physically separated western segment. On the eastern segment, however, there was a low occupancy-violation rate (less than 10 percent) and a safety problem caused by illegal weaving across the buffer shoulder. This produced an overall accident rate that was about the same as for a typical freeway. About 500 enforcement contacts are made per month. For the unseparated access lanes this illegal weaving is an even larger problem that has caused accident rates to double and created enforcement problems.

A safety problem at the ends of the busway was caused by increased congestion. An enforcement problem during stage 1 was caused by unclear signing. This problem was resolved at the beginning of stage 2. In summary, a physical barrier between the HOV lane and adjacent traffic lanes is desirable for safety, and adequate room must be provided for emergencies and enforcement activities.

PUBLIC OPINION

Public opinion has remained strongly positive. Surveys were done of busway carpoolers, bus riders, noncarpoolers who use the freeway lanes, and households in the corridor. Most bus riders said that the busway

Table 1. Development of equivalent costs and revenues.

Item	Additional Freeway Lane ($)	Actual Busway ($)	Low-Cost Busway ($)	Low-Cost Reversible Busway ($)
Capital costs				
Rights-of-way				
East segment	3 400	8 600	8 600	8 600
West segment	2 000	4 400	2 400	2 400
Lane construction				
East segment	7 300	7 900	7 900	8 000
West segment	3 200	11 900	3 400	3 400
Railroad relocation				
East segment	1 700	4 700	4 700	4 500
West segment	0	1 500	0	0
Ramps and tunnels				
East segment	600	3 200	600	600
West segment	0	-[a]	-[a]	-[a]
Station construction				
El Monte	0	3 800	3 800	3 800
Hospital and college	0	1 100	0	0
Project planning, design, and implementation	3 000[b]	8 100	5 000[b]	5 100[b]
Bus purchases				
Initial purchase—100	0	4 700	4 700	4 700
Replacement in 1990—150	0	7 000	7 000	7 000
Total—1972 dollars	21 200	66 900	48 100	48 100
Total—1977 dollars[c]	29 400	94 900	67 400	67 400
Annual operating costs				
Roadways	84	150	175	110
Terminals	0	350	280	280
Buses	0	3 830	3 830	3 830
Enforcement	77	77	77	77
Total	161	4 407	4 362	4 297
Less annual revenues	-0	-1 500	-1 400	-1 400
Net annual operating costs—1977 dollars	161	2 907	2 962	2 897
Equivalent annual capital costs[d]	1 388	4 736	3 262	3 262
Total equivalent annual costs—1977 dollars	1 549	7 643	6 224	6 159

[a] Ramps included in lane construction.
[b] These are estimated costs in 1972. Cost in 1978 would be almost double.
[c] Inflated by using Federal Highway Administration Highway Construction Cost Index (5, p. 631).
[d] Annualized equivalent of capital costs, less residual value of right-of-way (estimated equal to the original cost, in constant 1977 dollars).

should be open to carpools and that carpools have not hurt bus service. Noncarpoolers on the freeway lanes said that the busway should be open to both buses and carpools and that the busway was a good investment of taxpayer's money. Press coverage of the busway has been infrequent but positive. The busway is not controversial.

COST-EFFECTIVENESS

To form a basis for an evaluation of cost-effectiveness, the goals of the busway project were identified as

1. Provide added corridor capacity,
2. Reduce environmental impacts of corridor travel,
3. Improve the level of service for corridor travelers,
4. Reduce the personal cost of travel,
5. Improve the safety of corridor travel, and
6. Provide for future contingencies (e.g., a future rail line).

Measures of effectiveness (MOEs) were identified for each of the goals, and data were gathered to measure the degree of attainment of each of the goals during bus-only and mixed-mode operations.

To provide a better basis for future decision making, several hypothetical alternatives as well as the existing busway were included in this analysis. These included an additional freeway lane, a low-cost busway to take full advantage of what we have learned from this busway demonstration experiment, and a low-cost, reversible-lane busway similar to the Shirley Highway busway near Washington, D.C. Cost estimates were then made for the existing busway and for the three alternative options (see Table 1).

By using the above cost estimates and MOEs, the cost-effectiveness of the four options, under bus-only and mixed-mode operations, was evaluated. Mixed-mode operations were found to be generally more cost effective than bus-only operation, mainly because the relatively fixed costs were spread among more users, all of whom gained some benefits. The only exception was with regard to safety.

The busway was superior to the additional freeway lane option in the reduction of user costs, improvement of level of service, reduction of environmental impacts, and provision for future contingencies. There was no difference with regard to safety, and the freeway was more cost effective for providing added capacity. The low-cost busway options were a little more cost effective than the existing busway.

The greatest monetary benefit of the busway is the savings in user costs that result from reduced vehicle use by those new carpoolers and bus riders attracted to the busway. These user cost savings (for busway-induced carpoolers and bus riders only) cover two-thirds of the annual (capital and operating) costs of the busway.

Most of the above conclusions, however, would probably change dramatically if operating conditions on the adjacent freeway were to change dramatically (e.g., because of ramp metering or freeway widening).

CONCLUSIONS AND IMPLICATIONS FOR FUTURE BUSWAYS

This demonstration project has shown that busways can be cost effective, noncontroversial, and attract substantial numbers of solo automobile drivers to buses and carpools.

Busways would be most cost effective in bus-only operations if sufficient demand existed to fully utilize available capacity. When sufficient bus ridership demand does not exist, or when its development is uncertain, carpools may be added to increase the cost-effectiveness of busways with only minor impacts on bus operations. When bus demand is uncertain, the busway design should permit carpools to be added, limited, or removed as circumstances change during the life of the busway.

Demand data from this project have shown that a properly designed busway can attract a mode share similar to that of a comparable rail facility, at substantially less cost. The collection and distribution function served by the same busway buses reduces or eliminates the transferring required for a typical rail trip. The ability to increase cost-effectiveness by the addition or deletion of carpools makes a busway more adaptable than rail to changing or uncertain future circumstances. Of course, if total demand grows beyond the busway capacity, conversion to a higher-capacity rail line is possible.

For maximum cost-effectiveness, each major aspect of the busway design should be examined to determine that its cost is justifiable in terms of the additional users that it will attract. To minimize adverse impact, busways should be physically separated from adjacent freeway traffic and should not begin or end at places where the freeway will be congested—where these features can be achieved in a cost-effective manner.

Finally, busways are most appropriate for congested freeway corridors. If congestion does not exist or is eliminated, much of the attractiveness, and effectiveness, of the busway would be lost.

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Abridgment

Analysis of Bus Systems to Support Rail Rapid Transit

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This abridgment describes an evaluation of alternative bus systems that will serve as line-haul and feeder service for the Metropolitan Dade County Stage 1 Rapid Transit System (Miami area). The weighted derivative (sensitivity) of transit ridership is defined and computed for all study-area zones, zone pairs, districts, and district pairs. Then a comprehensive transit system is determined for the study area to aid in the planning process. These two concepts are applied to a large urban area by using the urban transportation planning system (UTPS) and UTPS-compatible programs.

Transit planning by use of UTPS for large urban areas generally precludes the use of optimization techniques in the design of bus route systems. The large networks, long computer execution times, and impenetrability of the UTPS programs all combine to make optimum use of UTPS at the detailed planning level difficult. Previous studies of optimization concepts generally dealt with smaller networks that have fewer than 100 nodes (1-3). The concept of the weighted derivative is motivated by the desire to use a gradient-type interactive approach to make changes in the bus route system. Knowledge of the potential change in ridership due to changes in travel disutility can guide the planner in making changes to increase ridership at the least cost. Although the approach used did not iterate in the usual sense, the information provided gives new insight for the two route systems studied and helps explain why one is superior to the other.

The concept of a comprehensive transit system is not new, but its application in a UTPS setting is (4,5). Sometimes called an ubiquitous system, a comprehensive transit system is an abstract concept defined by the following service characteristics:

1. It covers the entire service area,