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Foreword

This volume addresses the operational aspects of public transportation and presents new research. In each category, new ideas are explored and improved practices discussed. Potential application is real and holds significant promise of improved utility and better customer service.

The papers are based upon presentations at TRB's 74th Annual Meeting in January 1995 in Washington, D.C., and have been reviewed by peers (practitioner and academic) in the field of public transportation, in accordance with established Transportation Research Board procedures.

In Part 1, Bus, Paratransit, and Electric Trolley Bus, research covers 10 topics. As systems grow, it is important to study service changes, as in the case of feeder bus service to the Miami, Florida central business district (Hinebaugh and Boyle). On the West Coast, electric bus operations are evaluated as a new technology (Chira-Chavala et al.). Private bus service in Seoul, Korea, is undergoing service pressure from new subway lines and the private automobile (Won). To speed bus service, different bus priority at traffic signals technology is evaluated in Portland, Oregon (Hunter-Zaworski et al.). Still, maximizing scheduled use of transit vehicles is quite a challenge (Ceder) to model, as well as determining the optimal mixed bus fleet in urban service (Lee et al.). For paratransit, there is need to understand its role in the provision of transit service in developing countries (Shimazaki and Rahman). Electric trolley bus economics (Tennyson), evaluation of intersection configurations (Schwartz et al.), and electric magnetic fields (Fisher) are explored as well.

In Part 2, eight topics of Rail, Intermodal, and Light Rail research are presented. In Chicago a new CBD-Midway Airport line opened and has increased ridership overall in the corridor (LaBelle and Stuart). Street-running transit (rail transit, interurban, streetcar) is evaluated as a guide to the future (Levinson). As more systems become commuter rail oriented, the alternatives of using diesel or electric power must be decided (Sulkin). Other aspects of rail include evaluation of intermodal passenger transfer facilities (Horowitz and Thompson), rail access to airports (Mandalapu and Sproule), and track noise mitigation (Chen). In Calgary, Canada, light rail transit safety (Colquhoun et al.) and in San Jose, California, light rail collision accidents (Porter et al.) are analyzed.

Research in public transportation operations has clearly expanded in the last several years. There is much of interest to report.

PART 1

Bus, Paratransit, and Electric Trolley Bus

Metromover Extensions and Downtown Bus Service in Miami

DENNIS HINEBAUGH AND DANIEL K. BOYLE

The results of survey of feeder bus service in the Miami Central Business District (CBD) serving the elevated Miami Metromover downtown fixed-guideway circulator system are analyzed. Two extension legs of the Metromover (Omni and Brickell) opened in May 1994. The original plans for the Metromover extensions recommended that all CBD-oriented bus routes that operated in proximity to the new extensions be truncated at those locations. According to the original plans, the Metromover would become the major collector and distributor for Metrobus routes serving the CBD, as it currently functions for the Metrorail service. The purpose of this study was (a) to present the current operating characteristics of Metrobus service to and within the Miami CBD, (b) to analyze the impacts on existing bus riders for both travel time and cost introduced by the transfers from bus to mover on the opening of the new extensions, and (c) to set priorities on bus routes for potential truncation. The report's recommendations include an incremental approach for route truncation, with the prioritization process developed in this study as a guide. This process considers ridership, percentage of riders who are elderly or have a physical disability, transfer activity, and differences in travel time. It is also suggested that service kilometers reduced as a result of route truncation be put back into Metrobus service.

This study analyzed the results of a survey of feeder bus service in the Miami Central Business District (CBD) serving the elevated Miami Metromover downtown fixed-guideway circulator system. Two extension legs of the Metromover (Omni and Brickell) opened in May 1994. The original plans for the Metromover extensions recommended that all CBD-oriented bus routes that operated in proximity to the new extensions be truncated at those locations. As a result, a major bus transfer facility was constructed at the Omni Metromover Station, and bus bays were included in the construction of the Brickell Metromover Station shared with a Metrorail (heavy rail) station. According to the original plans, the Metromover would become the major collector and distributor for Metrobus routes serving the CBD, as it currently functions for the Metrorail service.

The purpose of this study was (a) to present the current operating characteristics of Metrobus service to and within the Miami CBD, (b) to analyze the impacts on existing bus riders for both travel time and cost introduced by the transfers from bus to mover on the opening of the new extensions, and (c) to set priorities on routes for potential truncation.

The first section of this paper presents background information regarding the Metromover system, particularly the Omni and Brickell extensions. The second section is a description of the operating characteristics of current Metrobus service into and within the Miami CBD, including the results of an on-board survey of riders within the Omni and Brickell corridors. The third section contains an analysis of the impacts of truncating CBD bus routes along the new Metromover extensions. Changes in travel time, frequency of transfers, and capacity of the Metromover stations are all included in this section, which concludes with the development of a prioritization process for route truncation. Recommendations are offered in the final section.

The prioritization process summarized in this project may be used when developing long-term corridor alternatives (i.e., railways and busways) in which existing local bus service could be truncated or rerouted. This process follows a logical sequence of data collection and analysis that can be defended at public hearings and presentations to policy making boards. The Dade County experience suggests that the political aspects of the decision making process must be taken into account along with the technical aspects. From a technical perspective, the Metromover's function as the distributor of CBD-bound trips should be maximized to promote the efficient operation of the overall transit system. This perspective strongly supports the truncation of CBD bus routes operating in proximity to the Metromover extensions. Early in this study, however, it became obvious that this action was politically infeasible. The prioritization process is one possible way of blending the two perspectives by identifying the most promising routes to truncate and by presenting an incremental approach that permits adjustments in response to successes or failures of specific actions.

BACKGROUND

In February 1988, the Metro-Dade Transit Agency (MDTA) in Dade County, Florida, completed the Final Environmental Impact Statement (FEIS) in cooperation with the U.S. Department of Transportation for the extension of the existing Metromover system. In May 1978, the Urban Mass Transportation Administration (UMTA) approved funds for the engineering of the Metromover system under the federally sponsored downtown people mover program. By 1979, a Metromover system alignment had been developed. The project was then separated into two parts. Final design for the initial 3.06-km (1.9-mi) core area loop, including nine stations, was started immediately. The core area loop became operational in April 1986. The remaining segment consisted of two extension legs serving the Omni and Brickell business areas north and south of the core loop. Each extension has six stations. On May 27, 1994, the Omni and Brickell extensions to the Metromover system began operation. Figure 1 details the guideway alignment and station locations for the entire Metromover system.

The Metromover system, including the two extensions, is proposed to continue to operate revenue service during the same hours as the Metrorail system. The proposed span of service is from approximately 5:30 a.m. to midnight daily.

Center for Urban Transportation Research, College of Engineering, University of South Florida, 4202 East Fowler Avenue, ENB 118, Tampa, Fla. 33620.

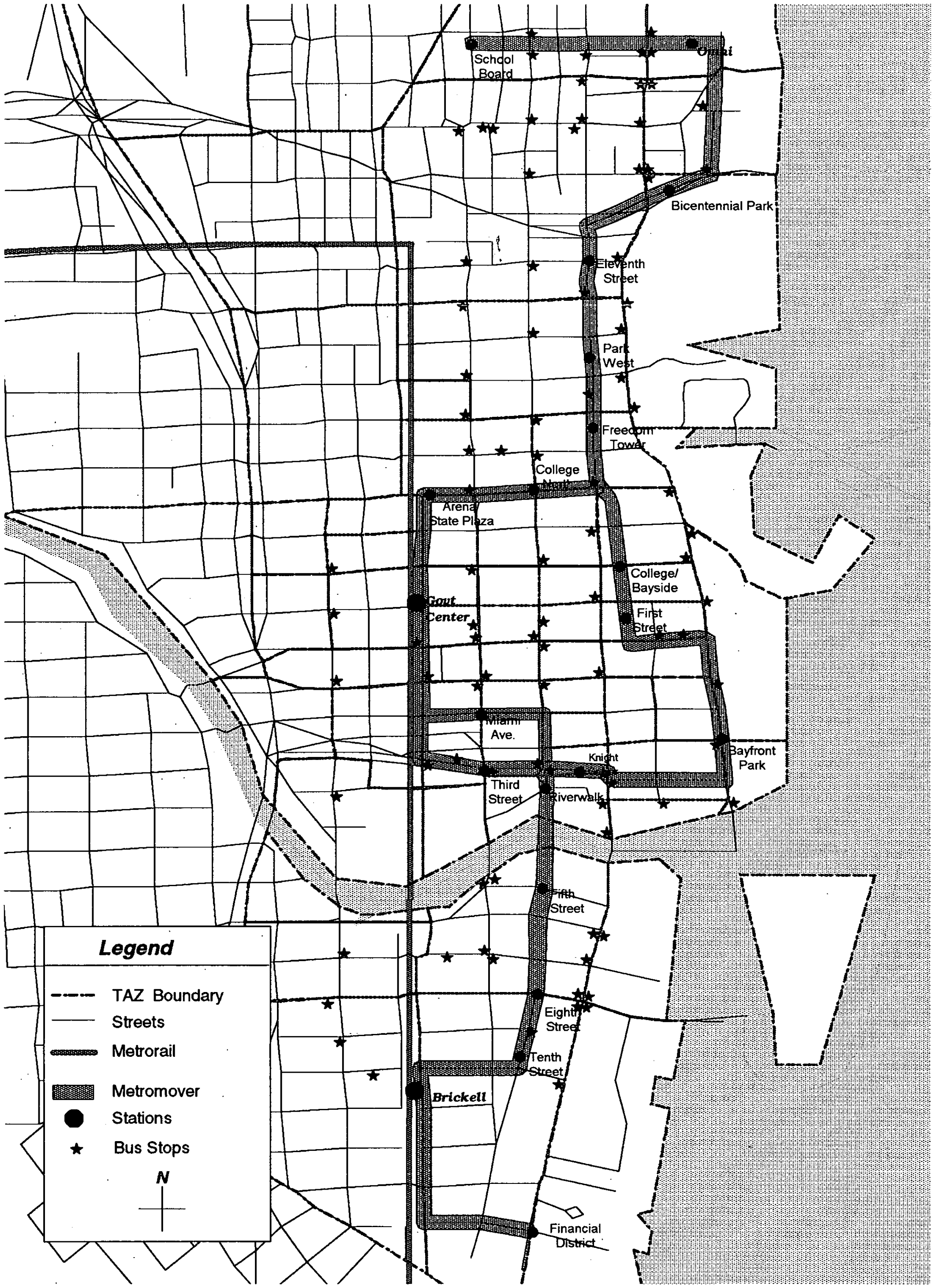

FIGURE 1 Miami CBD.

The existing Metromover system operates an outer loop in a counterclockwise direction and an inner loop in a clockwise direction. The two extension legs use the outer loop portion of the existing system. The Omni extension, starting at the School Board Station, travels through the five remaining extension stations and enters the outer loop at the College North Station. The Omni route then follows the outer loop of the core system, exits the core loop after serving the College/Bayside Station, and travels north back to the School Board Station. The total Omni outer loop round trip travel time is approximately 27 min.

The Brickell extension, starting at the Financial District Station, traverses through the five remaining extension stations and enters the outer loop of the core system at the Knight Center Station. The Brickell route then continues counterclockwise around the outer

loop and returns to the Brickell extension after serving the Third Street Station. The total round trip running time for the Brickell outer loop is approximately 24.5 min.

The inner loop routing of the core system is not affected by the two extension legs. The inner loop service operates with a 2.2-min headway in the a.m. (7:00 to 9:30 a.m.) and p.m. (3:30 to 7:00 p.m.) peak periods, and a 2.7- to 3.6-min headway at other times. Each extension leg operates on a 3.4-min headway during the a.m. and p.m. peak periods. Service in the midday period (9:30 a.m. to 3:30 p.m.) operates on a 4.2-min headway, whereas service before 7:00 a.m. and after 7:00 p.m. operates on a 5.8-min headway. The combined headway on the outer loop is 1.7 min in the a.m. and p.m. peak periods and 2.1 min in the midday peak period.

The original FEIS plans for the Metromover extensions recommended that all CBD-oriented bus routes that operate in proximity to the Omni and Brickell Metromover stations be truncated at those locations, requiring a transfer to the Metromover system for completion of a trip into the core of the CBD. As a result, bus transfer facilities have been constructed at both of these stations. According to the original plans, the Metromover would become the major collector and distributor for Metrobus routes serving the CBD, as it currently functions for the Metrorail (heavy rail) service.

CBD METROBUS AND METROMOVER SERVICE

There are currently 21 Metrobus routes serving the Miami CBD. For the purpose of this study, the CBD is defined as the area within 0.40 km (1/4 mi) of the existing Metromover and the Omni and Brickell extensions. Of the 21 routes, 11 fall within the Omni extension corridor, 4 are within the Brickell extension corridor, and 5 enter the CBD from the west. One express bus route has multiple branches and enters the CBD from each of the three corridors. Two routes serve both extensions and are shown in Table 1 under their primary entry corridor.

Table 1 presents the current weekday bus route service levels, including hours of operation and bus trips and screen-line passenger counts by time period for the routes serving the Omni and Brickell corridors. The span of service in the CBD begins as early as 4:39 a.m. and runs as late as 2:14 a.m. Frequency of bus service by route within the CBD ranges from a high of 40 inbound and 40 outbound trips in the midday on Route S, to a low of only one trip in the a.m. peak period on Route 6.

As presented in Figure 1, there are approximately 100 bus stop locations in the Miami CBD and Omni and Brickell downtown corridor areas. In the core of the CBD, most bus routes use the downtown bus terminal at SW 1st Street and SW 1st Avenue across from the federal building as their major destination and transfer point, with the major transfer location in the CBD for other routes in close proximity to the downtown terminal.

CBD Metrobus Ridership and Travel Times by Route

Table 1 also presents the results of an MDTA screen-line count of ridership into the CBD from both the Omni and Brickell areas performed in the Spring of 1993. Weekday ridership for the Omni and Brickell corridor routes during the three time periods surveyed totaled 25,003 riders. Ridership by time period ranged from a high of 1,435 on the inbound midday Route S to a low of 20 riders on the inbound a.m. Route 48. The Omni corridor bus routes carried approximately three times as many riders as the Brickell corridor routes.

Table 2 shows average bus travel times by time period along each path within the Omni and Brickell corridors into downtown. This information was derived from actual running times. There are three inbound and three outbound bus travel paths within the CBD for the Omni corridor routes. The Brickell corridor routes travel into and out of the CBD on four different paths. Note that a significant portion of each of the paths is shared with other paths, particularly within the core area of the CBD leading up to the CBD terminal and adjacent stops.

Bus travel times from the Omni Metromover Station area range from a low of 7 min for p.m. outbound service on Routes 9 and 10 to a high of 13 min in the midday period for outbound Routes K and T. Bus travel times from the Brickell Metromover Station range from a low of 5 min for outbound Route 8 in all three time periods to a high of 16 min for Route 8 in the inbound direction of the a.m. and p.m. peak periods. Travel times vary not only because of differing traffic conditions by time period and direction of travel, but also because of the directness of the routings. Some routes loop through the CBD before arriving at or after leaving the downtown terminal.

Downtown Miami Metrobus User Survey

In December 1993, Center for Urban Transportation Research (CUTR) and MDTA staff conducted a survey of Omni and Brickell corridor bus riders. Surveys were distributed during the a.m. (6:00 a.m. to 9:59 a.m.), midday (10:00 a.m. to 2:59 p.m.), and p.m. (3:00 p.m. to 6:59 p.m.) periods. Different survey forms were used for trips into and out of downtown.

The surveys were randomly distributed on all routes during all time periods and in both directions of travel. Surveyors boarded a bus at random at the Omni or Brickell location and handed out questionnaires to all passengers. In most cases, the surveyor remained on the bus for its outbound trip and continued distributing surveys to all passengers until reaching the Omni or Brickell locations. The surveyors then boarded the next inbound bus and continued the process.

Survey responses were weighted according to the screen-line ridership counts by route, direction, and time of day (see Table 1). The weighted survey frequencies for the three time periods total 25,003 trips.

As shown in Figure 2, 42 percent of the Omni and Brickell corridor bus riders paid their fare in cash, and 27 percent used a Metropass. Twenty-five percent of the passengers paid a discounted fare. According to the on-board survey performed for the entire Metrobus system in 1993, 65 percent of bus passengers pay by cash, and only 14 percent use a monthly Metropass. Therefore, CBD-oriented bus passengers are twice as likely to use a Metropass in comparison with systemwide Metrobus passengers. Passengers traveling to the CBD may have more regular travel patterns related to the work commute than other passengers, making purchase of a Metropass more feasible.

Altogether, 53 percent of downtown Metrobus riders transferred to or from another bus, Metrorail, or Metromover, whereas 44 percent walked to or from the bus. Among the individual categories shown in Figure 2, the most common responses were a transfer to or from another bus (34 percent) and a short walk (34 percent).

Passengers were asked whether they would transfer to or from the new Metromover extensions to complete their trip if the Metromover reduced travel time or if the transfer was free. Figure 2 shows that 77 percent stated they would use the Metromover if it saved time, whereas 67 percent would use Metromover if the transfer was

TABLE 1 Weekday Bus Route Service and Ridership Levels (Omni and Brickell Corridor Routes)

		Weekday Bus Trips			
Route	Span of Service	AM (6-10am)	Midday (10am-3pm)	PM (3-7pm)	Avg Weekday Ridership
OMNI CORRIDOR					
3	4:45am - 1:17am				
inbound		12	15	12	1,221
outbound		12	15	12	1,412
9	4:41am - 11:58pm				
inbound		14	7	14	525
outbound		14	7	14	653
10	5:09am - 12:27am				
inbound		6	9	6	416
outbound		7	8	6	395
16	5:08am - 11:15pm				
inbound		12	15	12	998
outbound		12	15	12	957
C	4:52am - 12:51am				
inbound		12	15	12	934
outbound		12	15	12	605
K	5:08am - 11:25pm				
inbound		12	15	13	961
outbound		12	15	12	587
M	5:39am - 11:24pm				
inbound		8	10	8	600
outbound		8	10	8	244
S (1)	4:51am - 2:14am				
inbound		30	40	32	3,055
outbound		30	40	32	2,471
T	4:52am - 10:08pm				
inbound		11	10	12	858
outbound		11	10	12	674
93	6:00am - 7:08pm				
inbound		11	1	16	740
outbound		15	4	13	596
				Total	18,902
BRICKELL CORRIDOR					
8	4:39am - 12:48am				
inbound		28	20	31	1,338
outbound		28	20	31	1,720
24	4:40am - 12:40am				
inbound		16	20	14	819
outbound		16	20	14	1,055
48	5:06am - 8:31pm				
inbound		4	5	3	142
outbound		4	5	3	186
B	5:50am - 8:43pm				
inbound		9	7	10	388
outbound		10	9	9	453
				Total	6,101

Source: MDTA 11-07-93 Schedules; Spring 1993 Survey.

free. It should be noted that survey respondents generally overstate their intentions to change their behavior when answering "stated preference" questions. Nevertheless, it is interesting to note that travel time savings induce a greater willingness to use Metromover than a free transfer.

Approximately 15 percent of the survey respondents answered Question 7, which asked riders to specify on a map provided on the back of the survey their final destination or the origin of their trip in downtown Miami. These results were then coded by traffic analysis zone (TAZ).

The most common origin and destination zones were Zones 640 and 644. The Metro-Dade Cultural Center, which contains the main county library, is located in Zone 640. Other high-frequency destinations and origins are in or adjacent to a corridor bounded by East Flagler Street and SE 1st Street.

IMPACTS OF BUS ROUTE TRUNCATION

Downtown Miami Metrobus Transfer Analysis

In January 1994, MDTA collected transfers from operators of CBD-oriented bus routes. Between 30,000 and 40,000 transfers were collected. Nearly 15,000 transfers occurred between the CBD-oriented routes, as well as between these routes and Metrorail. There were 10,320 bus-to-bus transfers. The greatest number

TABLE 2 Weekday Bus Route Travel Times (Omni and Brickell Corridor Routes)

		Minutes		
Path from Omni/Brickell Station Area	Route Number(s)	AM (6-10am)	Midday (10-3pm)	PM (3-7pm)
OMNI CORRIDOR				
Inbound from Omni Station area to Biscayne Blvd to Flagler St to CBD Terminal.	3, 16, 93X C, M, S	10	12	12
Inbound from Omni Station area (NE 2nd Ave and NE 14th St) to NE 1st St to SW/NW 1st Ave (CBD Terminal).	9, 10	8	11	10
Inbound from Omni Station area to NE 2nd Ave to Flagler St to SW/NW 1st Ave (CBD Terminal).	K, T	9	12	11
Outbound from CBD Terminal to SW/SE 1st St to Biscayne Blvd to Omni Station area.	3, 16, 93X C, M, S	10	10	10
Outbound from CBD Terminal to SW/SE 1st St to NE 1st Ave to NE 14th St.	9, 10	8	12	7
Outbound from CBD Terminal to SW/SE 1st St to NE 1st Ave to NE 14th St to Omni Station area.	K, T	9	13	8
BRICKELL CORRIDOR				
Inbound from Brickell Station to SW 8th St to S. Miami Ave to SE 4th St to NE 1st Ave to NE 6th St to Miami Ave to Flagler St.	8	16	15	16
Inbound from Brickell Station area (SW 13th St and SW 2nd Ave) along SW 13th St to Brickell Ave to SE 4th St to SE 3rd Ave to SE 2nd St to SW 1st Ave to SW/SE 1st St.	24	12	14	12
Inbound from SE 13th St and Brickell Ave along Brickell Ave to SE 4th St to SE 3rd Ave to SE 2nd St to SW 1st Ave to SW/SE 1st St.	48	10	10	10
Inbound from Brickell Station area along SW 1st Ave to SW 13th St to Brickell Ave to SE 4th St to SE 3rd Ave to SE 2nd St to SW 1st Ave to SW/SE 1st St.	B	13	11	9
Outbound from Miami Ave and Flagler St along Miami Ave to SW 1st Ave to Brickell Station.	8	5	5	5
Outbound from SW/SE 1st St and SW 1st Ave along SW/SE 1st St to SE 2nd Ave to Brickell Ave to SW 13th St to SW 2nd Ave.	24	7	10	11
Outbound from SW/SE 1st St and SW 1st Ave along SW/SE 1st St to SE 2nd Ave to Brickell Ave to SW 13th St.	48	7	7	8
Outbound from SW/SE 1st St and SW 1st Ave along SW/SE 1st St to SE 2nd Ave to Brickell Ave to SW 13th St to SW 2nd Ave to SW 11th St to SW 1st Ave and into the Brickell Station.	B	11	11	9

Source: Section 15 Ridechecks, 1993-94; 11-07-93 Rotary Schedules. (Note that Routes 24, 48, and B travel times and paths are prior to temporary rerouting for Brickell Bridge reconstruction.)

of transfers was from Metrorail (2,318), and the second greatest was from Route S (1,788).

There were 1,419 transfers occurring from an Omni bus route to a Brickell bus route. This represents 13.8 percent of the total CBD bus-to-bus transfers reported. The highest volume of transfer activity through the CBD from Omni routes to Brickell routes occurs from Routes S to 8, 3 to 8, and S to 24. There were 1,925 transfers from Omni routes to a westbound route, representing 18.7 percent of the total bus-to-bus transfers in the CBD.

There were 2,331 transfers occurring from a Brickell route to an Omni route. This represented 22.6 percent of the total CBD bus-to-bus transfers. The highest volume of transfers from Brickell routes to Omni routes occurred from Routes 8 to S and from 24 to S. A total of 263 transfers occurred from a Brickell route to a westbound route, representing only 2.3 percent of the total reported CBD bus-to-bus transfers.

The transfer analysis suggests that significant numbers of transferring bus riders would be affected by route truncation. These riders would have additional transfers (bus to Metromover to Metromover to bus, as opposed to the current bus to bus).

Station Capacity

The Omni bus terminal adjacent to the Omni Metromover Station opened in May 1994. The terminal consists of 10 sawtooth bus bays

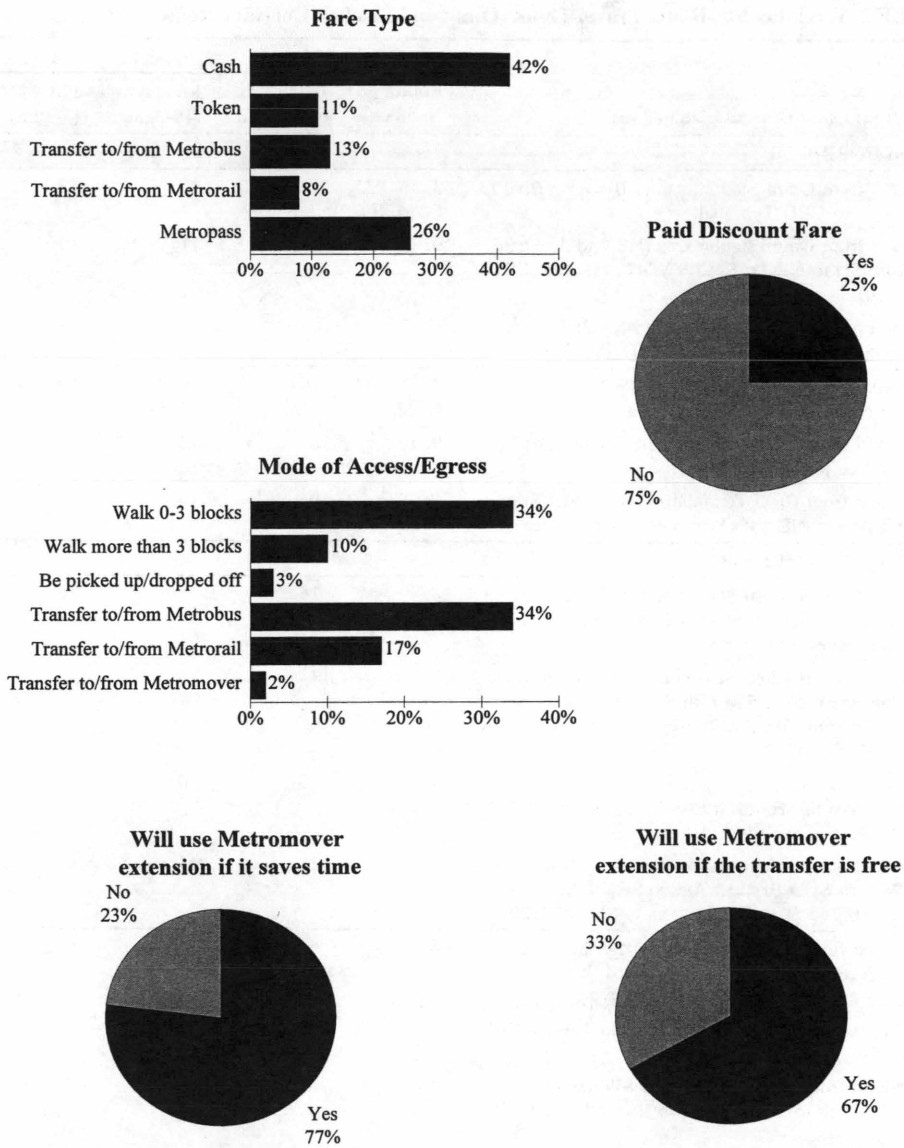

FIGURE 2 Downtown Miami Metrobus user survey.

surrounding an island with shelters and benches. This facility also includes restrooms for the drivers and a public information booth. Passengers must cross a bus-only roadway inside the terminal to enter the Omni Metromover Station.

Table 3 presents the weekday bus route volumes for the Omni and Brickell corridor routes that will directly serve the stations during the a.m., midday, and p.m. periods. If no routes are truncated, there would be a total of 919 bus trips into the Omni bus terminal in the three time periods combined. As bus routes are truncated, only the outbound trips entering the terminal would be eliminated. The highest number of bus trips (85) occurs in the p.m. peak hour. This number represents 8.5 buses per bus bay in the p.m. peak hour, or one bus entering a bus bay approximately every 7 min.

If all the corridor routes were truncated, then only the 459 inbound bus trips would come through the bus terminal, with a high of only 42 buses per hour in the p.m. peak hour. This number represents 4.2 buses per bus bay in the peak hour, or one bus entering a bus bay approximately every 14 min. This number appears reasonable for 10 bus bays.

With 12 routes scheduled to use the Omni bus terminal, the following issues were identified as essential to effective operation until major route truncation occurs.

- Proper signage is needed to distinguish between inbound and outbound bus routes.
- Layover or recovery time could interfere with the productive use of the bus bay. The on-street bay on 15th Street has been designated for layover buses. MDTA's schedule policy of minimizing layover time in the CBD ameliorates this potential problem.
- Procedures for the *quick removal of a broken-down bus* must be developed to avoid affecting the flow of buses in the terminal.

Although some Metrobus passengers whose destination is immediately to the south of the Omni terminal may elect to walk to their

TABLE 3 Weekday Bus Route Service Levels (Omni and Brickell Corridor Routes)

Route	Weekday Bus Trips[a] AM (6:00am-9:59am) Total	AM Peak Hour	Midday (10:00am-2:59pm) Total	Midday Peak Hour	PM (3:00pm-6:59pm) Total	PM Peak Hour
OMNI CORRIDOR						
CBD Routes						
inbound	129	35	142	28	140	36
outbound	134	36	144	27	135	37
Through Routes (Routes F, Flagler Max)						
inbound	20	6	8	1	20	6
outbound	19	7	8	2	20	6
Total						
inbound	149	41	150	29	160	42
outbound	153	43	152	29	155	43
Total (in & outbound)	302	84	302	58	315	85
BRICKELL CORRIDOR						
CBD Routes						
inbound	57	16	52	11	58	16
outbound	58	16	54	10	57	16
Total (in & outbound)	115	32	106	21	115	32

[a]Peak hour for each time period is 7:30am-8:30am; 12:00pm-1:00pm; and 4:30pm-5:30pm.
Source: MDTA 11-07-93 Rotary Schedules.

destination if Omni corridor bus routes are truncated, approximately 1,000 passengers per hour are expected to transfer to the Metromover in the a.m. peak period. The anticipated level of service for the Omni leg of the Metromover is a 3.4-min headway operating with single-car trains with a crush-load capacity of 96 passengers per car. The projected 1,000 passengers per hour, therefore, correlates to 57 passengers per train. This represents a load factor of 59 percent of crush load for each train. This is an average for the a.m. peak period; the peak hour load factor will be higher. The Metromover system is capable of running two-car trains should ridership warrant the extra service.

The Brickell bus staging area consists of five sawtooth bus bays located on SW 1st Avenue adjacent to the east side of the Brickell Metrorail Station. The Brickell Metromover Station is approximately 122 m (400 ft) south of the bus bays. The on-street bus bays do not have bus shelters or seats.

As shown in Table 3, if no Brickell corridor routes are truncated at the Brickell Metromover Station there will be a total of 336 bus trips into the on-street bus bays in the three peak periods combined. The highest average peak hour number of bus trips is 32, which occurs in both the a.m. and p.m. peak periods. This number represents 6.4 buses per hour per bus bay, or approximately one bus using a bus bay every 9.5 min. The current five bus bays should have no problem handling the current level of service, and on truncation of Brickell corridor bus routes they should be able to operate very efficiently.

A total of 239 Metrobus passengers per hour are expected to transfer to the Metromover in the midday period. The anticipated level of service for the Brickell leg of the Metromover is a 3.4-min headway operating with single-car trains. Based on a Metromover crush-load car capacity of 96 passengers, the 239 passengers per hour in the Midday correlates to 14 passengers per car or a load factor of 15 percent. The load factor for the single busiest hour in the midday period will be higher but well within the capacity of the Metromover system.

Travel Time

The a.m. peak period inbound total travel times to the core CBD TAZs via Metrobus or Metromover were developed. The Metromover travel times are derived from computer simulation runs before the opening of the two extension legs. The Metrobus travel times are actual preopening times. All travel times include transfer time, wait time, and walk time. Wait time is equal to one-half of the headway time for the particular route or mode. The total travel times are to the centroid of a TAZ from either the nearest bus stop or Metromover station. Walk times were calculated using a speed of 4.0 km (2.5 mi) per hour. Many Metromover travel times included either a transfer to the other Metromover extension leg, or a transfer to the inner loop if such a transfer would result in a travel time savings. It is assumed that passengers traveling to the College/ Bayside, First Street, or Bayfront Park stations from the Omni leg would transfer to the inner loop at the College North Station. Similarly, passengers traveling to the Miami Avenue or Government Center stations from the Brickell extension would transfer to the inner loop at the Knight Center Station.

In all but two TAZs of the Omni corridor and eight in the Brickell corridor, the total travel time for Metrobus is less than Metromover in travel to the zone centroid. The difference in travel time between Metrobus and Metromover is accounted for by the walk time from Metrobus to the station platform, the wait time for the next Metromover train, and the egress walk time to street level from the platform.

Table 4 presents the AM peak period through trip travel times for Metrobus passengers before the opening of the Metromover extensions. This information was taken from 1992–1993 MDTA Section 15 ride-check reports. For comparison with the Metromover through trip travel time, these times are in-bus travel time only and do not include the wait time in transferring from one route to another. Total travel time from the Omni terminal to the Brickell

TABLE 4 Morning Peak Period Travel Time via Bus (Current Conditions)

Route Numbers	Minutes: Omni to CBD Terminal	CBD Terminal to Brickell[a]	Brickell to CBD Terminal Area	CBD Terminal Area to Omni[b]	Total Travel Time
3, 16, 93X, C, M, S	10	7	-	-	17
9, 10	8	7	-	-	15
K, T	9	7	-	-	16
8	-	-	16	9	25
24	-	-	12	9	21
48	-	-	10	9	19
B	-	-	13	9	22
Transferring from western routes	-	7	-	-	7
2, 7, 11, 21, 77	-	-	-	9	9

[a]Average AM peak period outbound travel time for Brickell corridor routes.
[b]Average AM peak period outbound travel time for Omni corridor routes.
(Note that, for comparison to Mover travel times presented in Table 5, neither table contains wait time for transfer to bus.)

terminal ranges from 15 to 17 min. Total travel time from the Brickell bus stop area to the Omni terminal ranges from 19 to 25 min. As noted in the table, the travel time from the CBD terminal to Omni or Brickell represents an average for the routes serving those corridors in an outbound direction. Table 4 is derived from information presented previously in Table 2.

Table 5 presents the a.m. peak period through trip travel time via the Metromover system. Total travel time is presented for the six possible bus and Metromover trip paths. Travel times range from a low of 16.8 min for the trips from the Omni terminal to the CBD bus terminal and from the CBD bus terminal to the Brickell bus stop, to a high of 26.4 min from the Brickell bus stop to the Omni

TABLE 5 Morning Peak Period Travel Time via Metromover

Trip Path	Minutes: Walk Time to Mover	Wait Time for Mover	Mover Travel Time	Walk Time to Bus	Mover to Mover Transfer Time	Mover Travel Time	Walk Time to Bus	Total Travel Time
OMNI BUS TO CBD BUS (Bus to Omni Mover to Government Center to CBD Bus Terminal)	2.0	1.7	9.1	4.0	n/a	n/a	n/a	16.8
OMNI BUS TO BRICKELL BUS (Bus to Omni Mover to Third St Station to Brickell Mover to Brickell to Bus)	2.0	1.7	11.2	n/a	1.7	5.7	4.0	26.3
BRICKELL BUS TO CBD BUS (Bus to Brickell Mover to Knight Center Station to Inner Loop to Government Center to Bus)	4.0	1.7	5.6	n/a	1.1	3.1	4.0	19.5
BRICKELL BUS TO OMNI BUS (Bus to Brickell Mover to College Station to Omni Mover to Omni to Bus)	4.0	1.7	10.0	n/a	1.7	7.0	2.0	26.4
CBD BUS TO BRICKELL BUS (Bus to CBD Bus Terminal to Government Center to Mover to Brickell Mover to Brickell Bus Stop)	4.0	1.7	7.6	4.0	n/a	n/a	n/a	17.3
CBD BUS TO OMNI BUS (Bus to CBD Bus Terminal to Government Center to Inner Loop to College/Bayside Station to Omni Mover to Omni to Bus)	4.0	1.1	3.2	n/a	1.7	7.2	2.0	19.2

(Metromover to Metrorail)	Minutes: Walk Time to Mover	Wait Time for Mover	Mover Travel Time	Walk Time to Metrorail	Total Travel Time
OMNI BUS TO METRORAIL (Bus to Omni Mover to Government Center to Metrorail)	2.0	1.7	9.1	1.0	13.8

TABLE 6 Morning Peak Period Travel Time Comparisons (Bus/Metromover Extensions)

	Minutes		
Trip Path	Mover Only	Bus Only	Difference
Omni Bus Terminal to Government Center			
- Routes 3, 16, 93X, C, M, S	13.8	13	+0.8
- Routes 9, 10	13.8	11	+2.8
- Routes K, T	13.8	12	+1.8
Omni Bus Terminal to Brickell Bus Terminal			
- Routes 3, 16, 93X, C, M, S	26.2	17	+9.2
- Routes 9, 10	26.2	15	+11.2
- Routes K, T	26.2	16	+10.2
Brickell Bus Bays to Government Center			
- 8	16.2	14[a]	+2.2
- 24	16.2	15	+1.2
- 48	16.2	13	+3.2
- B	16.2	16	+0.2
Brickell Bus Bays to Omni Bus Terminal			
- 8	25.9	25	+0.9
- 24	25.9	21	+4.9
- 48	25.9	19	+6.9
- B	25.9	22	+3.9

[a]Assumes riders on Route 8 would walk to Government Center from NE 1st Avenue and 1st Street instead of travelling loop to bus terminal.
(Note that this analysis assumes a one minute walk time from the Mover to the ground floor of Government Center and a three minute walk time from the CBD bus terminal to the ground floor of Government Center.)

bus terminal. Also presented in Table 5 is the Metromover to Metrorail total travel time from the Omni bus terminal to the Government Center Metrorail Station. Total travel time for this trip is projected to be 13.8 min in the a.m. peak period.

Table 6 is a comparison of the Metrobus and Metromover travel times presented in the two previous tables. For comparison, the trip path destined to the CBD assumes the passenger is going to the Government Center. As shown in this table, the Metrobus total trip times are less than the Metromover by 0.2 to 11.2 min. This does not imply that the Metrobus is a faster mode in terms of average speed, only that the total trip times, which include the walk and wait times associated in transferring from bus to Metromover, create an overall longer travel time by Metromover. A patron traveling from Omni to Government Center to transfer to Metrorail can make the trip by Metromover in approximately the same time as by bus.

Given the variations in the bus travel times, and the number of assumptions required for an analysis of this type, a difference of under 2 min is considered marginal.

RECOMMENDATIONS

Based on the information presented in this paper, the following recommendations are offered about the issue of Metrobus route truncation related to the opening of the Metromover extensions.

Truncation of Metrobus Service

The FEIS document for the Metromover project assumed the truncation of Metrobus service before entering the CBD. In this scenario, the Metromover system would be the distributor for Metrobus riders, similar to its current function for Metrorail riders. To lessen the impact of truncating all Metrobus service at once, it is recommended that the service truncations be phased in over an approximate 2-year period after the opening of the Metromover extensions in May 1994.

Table 7 presents a process for setting priorities for the Omni and Brickell corridor bus routes for truncation. Routes are prioritized only within the specific corridor. Factors considered in the prioritization process include total daily ridership, percentage of patrons who are over 65 years old or who have a physical disability, transfers, and difference in travel time between Metromover and bus. Although no single measure is specifically weighted to give it more importance, three measures include transfer activity and two measures include travel time comparisons. Routes were ranked from 1 to 10 (1 to 4 for Brickell corridor routes), and an average ranking was derived from these scores.

As can be seen from Table 7, Routes M, 16, and 93X (Biscayne Max) are ranked in the top third for route truncation in the Omni corridor. Route 48 ranks the highest in the Brickell corridor and Route B the second highest.

Aside from the technical process of ranking the routes for truncation, another factor to be considered in setting priorities for the routes is whether there is other bus service on this particular alignment into the CBD. Initially, this is not an issue for the top three Omni corridor routes or the top two Brickell corridor routes recommended for truncation.

Regarding the issue of whether to truncate all of the Omni and Brickell corridor routes as assumed in the FEIS, it is recommended that MDTA monitor the bus and mover ridership into the CBD and transfer activity after the first phase of truncations to determine the

TABLE 7 Priority Ranking of Route Truncation (Omni and Brickell Corridor Routes)

	Total Weekday Riders				Percent of Transfers from Omni/Brickell Buses						AM Peak Period Change in Average Travel Time To Government Center, Mover vs. Bus				
Route	To/From CBD[a]	Rank	% Seniors or Disabled[b]	Rank	To West-bound Bus	Rank	Between Buses	Rank	To Metrorail	Rank	In-vehicle minutes[c]	Rank	Passenger minutes[d]	Rank	Final Priority Ranking
OMNI CORRIDOR															
3	2,896	9	10%	3	1%	1	9%	8	6%	10	0.8	1	346	4	6
9	1,296	3	13%	7	3%	7	9%	8	18%	1	2.8	9	963	10	10
10	892	1	10%	3	3%	7	4%	1	16%	2	2.8	9	638	7	4
16	2,151	8	7%	1	3%	7	5%	2	8%	5	0.8	1	339	3	3
C	1,693	6	13%	7	2%	3	11%	10	9%	4	0.8	1	246	2	5
K	1,703	7	12%	5	2%	3	8%	6	8%	5	1.8	7	706	8	8
M	928	2	13%	7	1%	1	7%	4	7%	7	0.8	1	176	1	1
S	6,079	10	18%	10	2%	3	5%	2	7%	7	0.8	1	637	6	7
T	1,685	5	12%	5	2%	3	8%	6	7%	7	1.8	7	770	9	9
93X	1,336	4	8%	2	3%	7	7%	4	12%	3	0.8	1	390	5	2
BRICKELL CORRIDOR															
8	3,364	4	14%	3	3%	1	15%	3	10%	1	2.2	3	950	4	3
24	2,061	3	13%	1	5%	4	16%	4	1%	3	1.2	2	317	3	4
48	361	1	13%	1	3%	1	8%	1	3%	2	3.2	4	64	2	1
B	925	2	16%	4	4%	3	13%	2	1%	3	0.2	1	21	1	2

[a]Ridership by route from screenline counts for AM, Midday, and PM peak periods, factored up 10 percent for total weekday ridership.
[b]From the 1993 Metrobus On-Board Survey.
[c]Assumes average rider from Omni or Brickell travels to Government Center.
[d]Weighted by multiplying the difference in Mover/Bus "travel time" by total inbound AM peak period ridership.

extent to which patrons of the truncated routes are transferring to the Metromover or to another bus destined to the CBD, and also whether patrons of nontruncated routes are transferring to the Metromover.

Based on the travel behavior of bus and Metromover riders and other efficiency considerations, the decision about which additional routes to truncate can be made at that time.

It is recommended that any service kilometers truncated as a result of the Metromover extensions be put back into Metrobus service. This will improve bus service outside the CBD, reducing headways and decreasing a patron's total travel time. This can help to offset both the added travel time and the inconvenience of transferring to the Metromover at the Omni and Brickell stations.

Currently 10 of the 15 Metrobus routes analyzed operate service into or out of the CBD earlier or later than the proposed operating hours (5:30 a.m. to midnight) for the Metromover system. It is recommended that Metromover's hours of operation be revised to reflect the extended hours of the Metrobus service. If this is not possible, then arrangements must be made to operate these routes into the CBD during the late night and early morning hours.

The incremental approach to bus route truncation is appropriate for the Metromover extensions, given the inconvenience associated with an added transfer requirement and the travel time impacts. For a new light rail or heavy rail system, in which the length of the line-haul trip segment via fixed guideway can produce notable travel time savings, a major realignment of the bus network to feed the new rail line may be more sensible. The ultimate goal in Miami is to have the Metromover function as the downtown distributor. Over the next several years, the prioritization scheme should allow MDTA to reach this goal in large measure without engendering community opposition.

DISCUSSION OF PROJECT

Since the completion of the analysis presented in this paper, the Metromover extensions have opened for revenue service. During the first 6 months of operation, Metromover operated with a free fare and ridership averaged 18,500 riders per weekday, ranging between 14,000 and 21,000 riders. Since the recent initiation of the standard fare policy, which charges $0.25 per trip, ridership has averaged 16,000 per weekday.

Before the opening of the Metromover extensions, public hearings were held in connection with the truncation of bus service into the CBD as recommended in this analysis. On review by the political bodies of Dade County, a decision was made to proceed with the truncation of only one route at that time.

CUTR followed up this original work with an analysis of travel behavior of the riders of the expanded Metromover system. The purposes of this second analysis were to (a) monitor the bus-to-Metromover, bus-to-bus, and Metromover-to-bus transfer activity at both the Omni and Brickell Metromover stations after the opening of the extensions; (b) survey bus and Metromover riders at the Omni and Brickell stations to analyze the impacts of the extension

openings, including transfers and station destination; and (c) continue to update, based on the previous information, the prioritization of Metrobus route truncation.

This report found that riders remaining on the Metrobus routes feeding the new Omni and Brickell station areas did not use the Metromover system because the Metrobus was closer to their origin or took them closer to their final destination in the Miami CBD. The second, related reason was that they perceived the Metromover to take longer for their trip time. A number of riders also indicated that they did not want to transfer. A short walk was the most typical mode of access and egress. Finally, most passengers on the bus routes were traveling to or originating from the Government Center area.

The respondents to the Omni and Brickell stations Metromover survey used the Metromover system because it saved them time and brought them closer to their destinations. Many respondents stated they rode the Metromover because it was more pleasant to ride. As with the bus system, the majority of respondents reported a short walk as their mode of access. Finally, although the Omni Metromover respondents were generally traveling to the Government Center area of the Miami CBD, the Brickell riders were generally only traveling one to three stops north on the Metromover before alighting.

Finally, on the basis of the information presented in the follow-up report, no changes were recommended to the bus route truncation prioritization process and established priorities. Data have shown the importance of travel time and the negative attitudes toward transferring, two major factors of the prioritization process. However, based on the number of patrons gaining access to the Metromover by Metrobus, it is obvious that Omni Metrobus users are much more likely to adjust to route truncation at the Omni Station because of the proximity of the Metromover platform, as opposed to the long walk from the bus stop to the Metromover platform at the Brickell Station. This was recommended as a consideration when choosing between Omni and Brickell Metrobus routes for truncation.

Survey results suggest that passengers are making rational decisions based on their origin or destination within the Miami CBD and their perception of travel times in choosing whether to use Metrobus or Metromover. The more pleasant ride offered by Metromover is a less important factor than convenience and travel time savings. Anecdotal evidence suggests that not all Metrobus riders are aware of the Metromover extensions as an alternative way of getting around downtown.

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Electric Bus Operation and Evaluation in California

T. CHIRA-CHAVALA, D. EMPEY, M. PUVATHINGAL, AND C. VENTER

This study evaluated the performance, energy consumption, range, and costs of electric buses recently deployed around the campus of the University of California at Berkeley. These electric buses have a relatively low curb weight and purchase price compared with electric buses in operation elsewhere. The series-wound direct current motors of the electric buses result in poor hill-climbing ability. This study presents results of vehicle tests under controlled conditions, statistical models for hill-climbing speed, energy consumption in revenue service, and estimated vehicle range. It also compares capital, energy, and battery-replacement costs of the electric buses and diesel buses.

Vehicle emissions are a serious problem in California. The California Air Resources Board established a mandate requiring 2 percent of all vehicles sold in California by 1998, and 10 percent by 2003, to be zero-emission vehicles. Transit fleets represent an initial market niche for electric vehicles in the absence of more advanced batteries. The daily range requirements of transit vehicles are generally predictable, and existing bus garages can readily accommodate battery-recharging and battery change-out facilities.

The University of California at Berkeley (UCB) started deploying four medium-sized electric buses in late 1993 in fixed-route service around the campus perimeter (the perimeter route). This 4.4-km route, previously served by diesel buses, is a relatively low-speed bus operation because the route goes through built-up areas and downtown Berkeley. The UCB electric buses were manufactured by Electricar Inc.

OBJECTIVE

The objective of this study was to evaluate the performance, as well as the advantages and disadvantages, of the UCB electric bus operation using empirical data from revenue service runs and road tests under controlled conditions.

UCB ELECTRIC BUSES

Each UCB electric bus is 6.3 m long, 2.2 m wide, and 2.6 m high, with a 0.45-m floor height. It has one door and a wheelchair lift. The seating capacity is 16, plus 6 standees. The curb weight is 4680 kg, 29 percent of which is the weight of traction batteries; the rated gross vehicle weight is 6520 kg. Regenerative braking is activated whenever the throttle is released and the brake pedal is depressed. The specified maximum speed is 40 km/hr.

Traction power is provided by two 23-cm series-wound direct current (dc) motors and solid-state controllers. The dc motors have a nominal voltage of 120, maximum revolutions per minute (RPM) of 6,000, and maximum current of 400 amps. The motors are powered by four trays of lead-acid batteries, each tray consisting of ten 6-V U.S. Battery Deep Cycle batteries. The battery pack has 370 amp-hr (based on a 3-hr rating) and a 120-V nominal rating.

The charge in the battery pack decreases as the electric bus is driven. Each bus has spare battery packs to allow battery recharging to be done only at night, when electricity cost and demand are the lowest. A depleted battery pack can be exchanged for a fully recharged one at any time during the day. This battery change-out is accomplished with a specially designed forklift and can be done in 10 min.

PERIMETER ROUTE

The perimeter route is roughly rectangular, encompassing the campus (Figure 1). Four streets make up the sides of this rectangular: Shuttuck Avenue, Hearst Avenue, Piedmont Street, and Bancroft Way. The buses run in a one-way clockwise loop, covering 4.4 km per round trip.

The four streets making up the perimeter loop differ considerably from one another in road and traffic characteristics, such as number of lanes, roadway grade, average block length, amount of roadside development, pedestrian and traffic volumes, and percent of heavy vehicles (Table 1).

- Shuttuck Avenue. This is a very busy main street in downtown Berkeley. It is a four-lane divided avenue that is straight and almost flat. Curb parking is allowed on both sides. The street consists of very short blocks (130 m long on average). There are seven intersections, six of which have traffic signals.
- Bancroft Way. This busy street is south of the campus. It is a straight three-lane one-way street with long downhill slopes throughout. Curb parking is allowed on both sides. It has six evenly spaced intersections, three of which have traffic signals.
- Hearst Avenue. This is a four-lane street, two lanes of which are for parking. This street is unique because it consists of several steep upgrades of up to 12 percent. It has six intersections, one of which has a traffic signal.
- Piedmont Street. This street is much less busy than the other three streets. It is a winding two-lane street with mild uphills and downhills (up to ± 5-percent grade). There are two small intersections and no traffic signals.

SPEED CAPABILITY OF UCB ELECTRIC BUSES

Observed Speed Characteristics in Road Tests

Road tests under controlled conditions were conducted before the UCB electric buses were put into revenue service operation. These

University of California, Institute of Transportation Studies, 109 McLaughlin Hall, Berkeley, Calif. 94720.

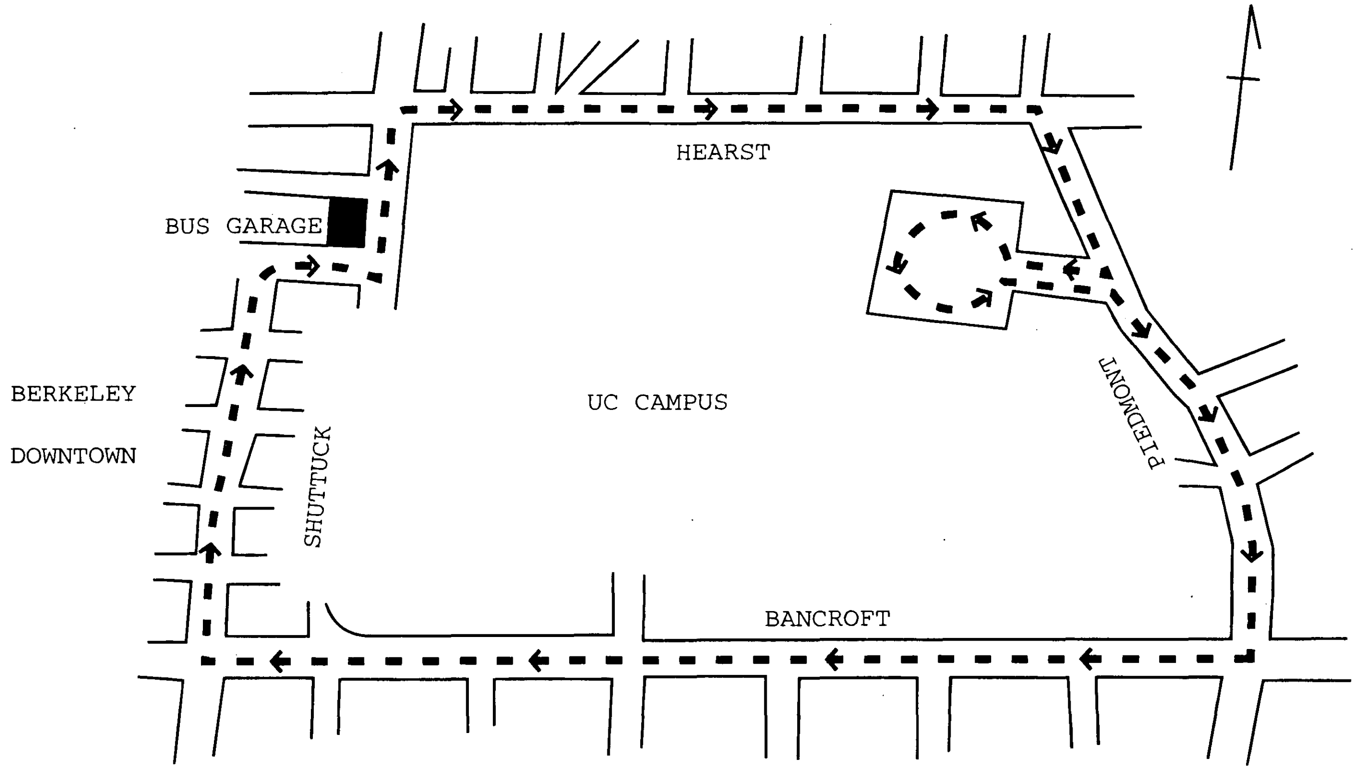

FIGURE 1 Diagram of perimeter route.

tests were conducted on a test track and on roads with little traffic. The bus was test-driven at a fixed driving cycle and carried no passengers (bus loading was accomplished with ballast of known weight). One test driver was employed for all of the road tests.

Results of the controlled road tests revealed an important power characteristic of the bus's series-wound dc motor (Figure 2). The motor developed peak power at about 15 km/hr, well below the manufacturer-specified top speed of 40 km/hr. As vehicle speed increased beyond 15 km/hr, the power decreased quickly. This characteristic has advantages and disadvantages. Because the power initially increased rapidly to the maximum value, the UCB electric bus will always have good initial acceleration from a stopped position. The limited power available at higher speeds also minimizes overall energy consumption and thus maximizes the driving range. On the other hand, the limited power at higher speeds results in poor acceleration at high speeds and at low speeds on steep upgrades.

TABLE 1 Characteristics of Streets Making Up Perimeter Route

	Street Characteristic	Shuttuck	Bancroft	Hearst	Piedmont
1.	Street length (km)	0.9	1.4	0.9	1.2
2.	Effective # of lanes	4	3	2	2
3.	Max grade (%)	+2	-5	> +11	± 6
4.	Aver block length (km)	130	230	150	600
5.	Intersections/km	7.8	4.3	6.7	1.7
6.	Signalized intersections/km	6.7	2.1	1.1	none
7.	Bus stops/km	2.5	3.0	3.5	0.8
8.	Shops and offices	very high	medium	low	none
9.	Pedestrians	very high	very high	medium	low
10.	Vehicle volume (vph)				
	- Afternoon peak	2500	2160	1420	1620
	- Off-peak	1880	1760	1040	1080
11.	% heavy vehicles				
	- Afternoon peak	2	4	3	2
	- Off-peak	5	10	9	6

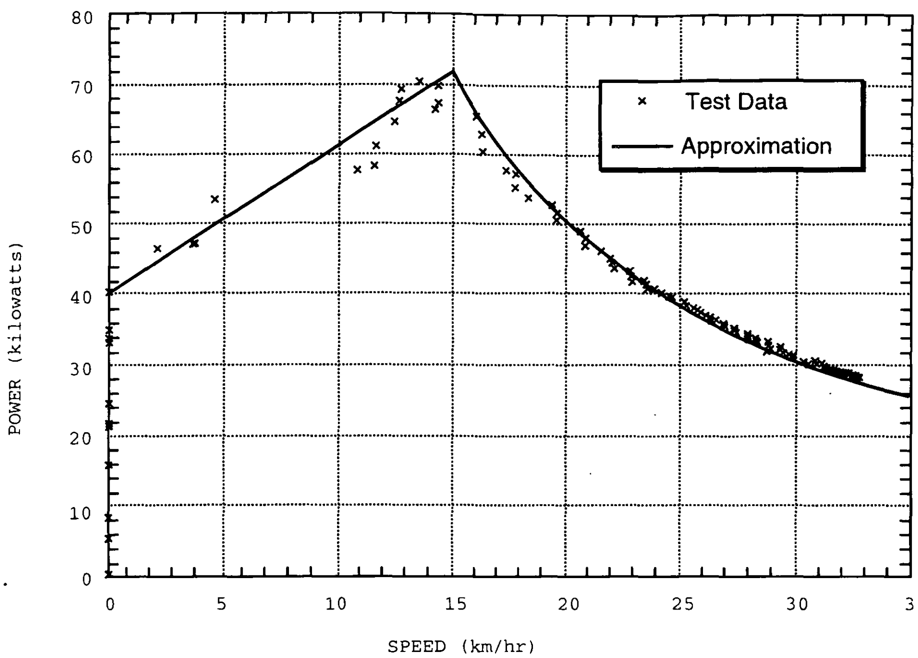

FIGURE 2 Power characteristics of motors of UCB electric buses.

Figure 3 shows the observed available power (with 680-kg loading) from the road tests and required power versus speed for upgrades of 0, 5, 10, and 15 percent. The required power for a 0 percent grade was observed in the road tests, whereas those for 5, 10, and 15 percent grades were derived from the following formula (assuming drivetrain efficiency of 100 percent).

$$P_G = P_0 + W \times g\,(G/100) \times V \quad (1)$$

where

P_G = required power for G percent grade (watt),
P_0 = required power for 0 percent grade (watt),
W = total vehicle weight (kg),
g = the gravity force (9.81 m/sec^2),
G = the percent grade, and
V = vehicle speed (m/sec).

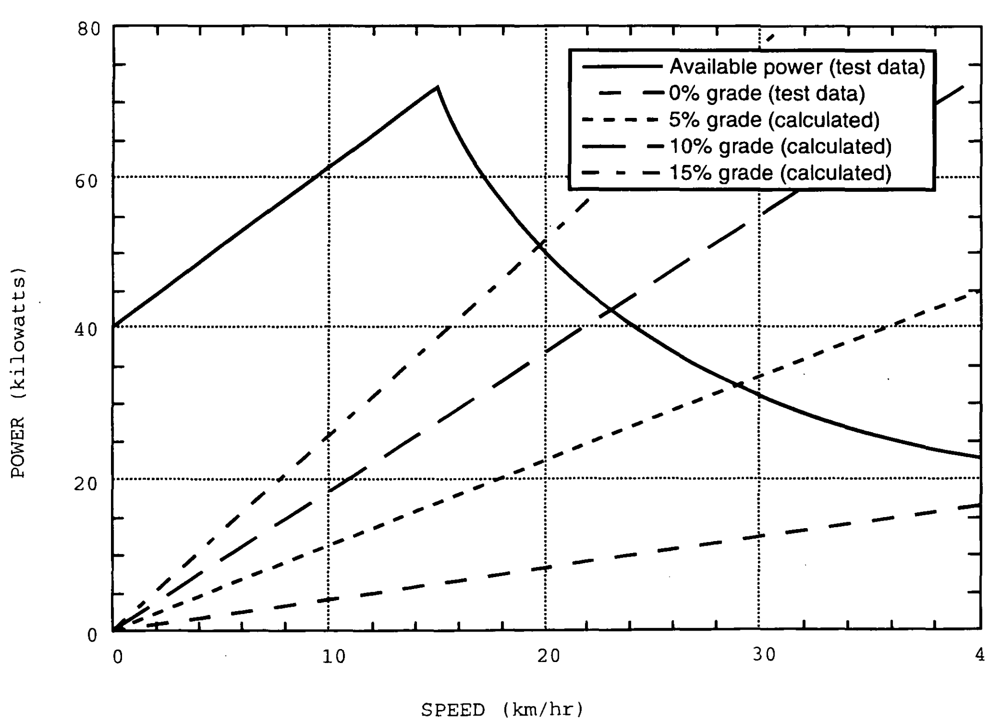

FIGURE 3 Available and required power for various speeds and upgrades.

The intersection between available and required power for a particular roadway grade indicates the upper limit of speed capability for that grade.

Results from the road tests also indicated that as the battery became more and more discharged, the available power decreased by as much as 10 to 15 percent.

Observed Effect of Battery Depth-of-Discharge (DOD) on Speed

DOD is defined as the percent of charge removed from the battery as the bus is driven. A higher DOD value indicates that less charge is available. Results of the controlled road tests indicated a nonlinear effect of the battery DOD on vehicle speed. That is, observed speed profiles for full and half-full batteries were similar. However, observed speed for a deeply discharged battery (with 80 percent DOD) was up to 10 percent lower than speeds for full and half-full batteries. This may be caused by the battery's ability to maintain output current well until it is deeply discharged.

Observed Effect of Payload on Speed

Controlled road tests were conducted to assess the effect of payload on vehicle speed. The results indicated that vehicle speed decreased slightly as loading increased.

Observed Acceleration Capability in Road Tests

Controlled road tests were conducted in which the UCB electric bus was driven up a 7 percent upgrade with a battery DOD of about 80 percent. The driver stopped the test bus approximately midway on the upgrade and then restarted the bus. The bus had no problem starting and accelerating from a stopped position on the 7 percent upgrade, even when the battery was deeply discharged.

Model for Hill-Climbing Speed in Revenue Service

The revenue service operation around the perimeter route is characterized by real-world driving cycles, frequent vehicle stopping and starting, variable passenger loading, different drivers (with different driving styles), variable roadway grades, variable traffic conditions, and other factors. The limited top speed of the UCB electric bus does not present a problem in revenue service runs on level roads. However, on steep upgrades along the perimeter route, speed could drastically decrease. Therefore, hill-climbing speed of the UCB electric bus is an important performance characteristic because it can affect adherence to the schedule, as well as users' perceptions of the electric buses.

A statistical model was developed to express hill-climbing speed in the revenue service operation as a function of various influencing independent variables. The dependent variable was the maximum attainable hill-climbing speed, defined as the maximum speed at which the bus could cruise while traveling on an upgrade. Road sections with grades greater than 0 percent were included in the modeling.

A computerized data-acquisition system was installed on the electric bus to record second-by-second vehicle speed, output current, and output voltage in revenue service runs.

Candidate independent variables included the percent grade, the length of grade, passenger loading, battery DOD, and time of day. Passenger loading was represented by the "load ratio," defined as the ratio of actual passenger loading to the manufacturer's allowable maximum payload. Passenger loading was derived from passenger counts multiplied by an assumed average passenger weight of 72 kg. The allowable maximum payload was the difference between the rated maximum gross vehicle weight and the curb weight. Battery DOD was computed for the beginning of each upgrade section. Time of day was represented by peak and off-peak hours, and was an indicator of the vehicular and pedestrian volumes. It was incorporated in the regression analysis as a dummy (0,1) variable.

The best-fit model for hill-climbing speed capability was found to be:

$$Y = 38.78 - 7.961\, X_1^{0.33} - 3.137\, X_2 \tag{2}$$

where

Y = maximum hill-climbing speed,
X_1 = percent upgrade, and
X_2 = load ratio.

The t-statistics for the coefficients of X_1 and X_2 were -15.73 and -3.68, respectively, indicating that both independent variables were statistically significant at most reasonable levels of the probability of Type I error (α). R^2 is 0.77, indicating that 77 percent of total variation in the dependent variable was explained by the estimated model. The estimated standard error was 2.08 and the sample size was 86.

This estimated model implied that maximum hill-climbing speed was lower for steeper upgrades and higher payload, as expected. Length of upgrade, battery DOD, and time of day were found to be statistically nonsignificant in revenue service. Figure 4 shows estimated hill-climbing speeds in revenue service operation plotted against the percent upgrade for three load ratios.

ENERGY CONSUMPTION

Observed Energy Consumption in Controlled Road Tests

Vehicle energy consumption is the dc energy drawn from the battery to drive the electric bus. It can be calculated from observed current and voltage as follows:

$$W = \int \mathrm{V} i \cdot dt \tag{3}$$

where

W = vehicle dc energy consumption (watt-sec),
V = voltage (volt),
i = current (amp), and
t = time (sec).

The controlled road tests indicated that observed vehicle dc energy consumption rates (per vehicle kilometer) were different between travel on level roads and travel on uphills; the rates were 0.78 and 0.82 kW · hr/km for level roads and 7 percent upgrades, respectively.

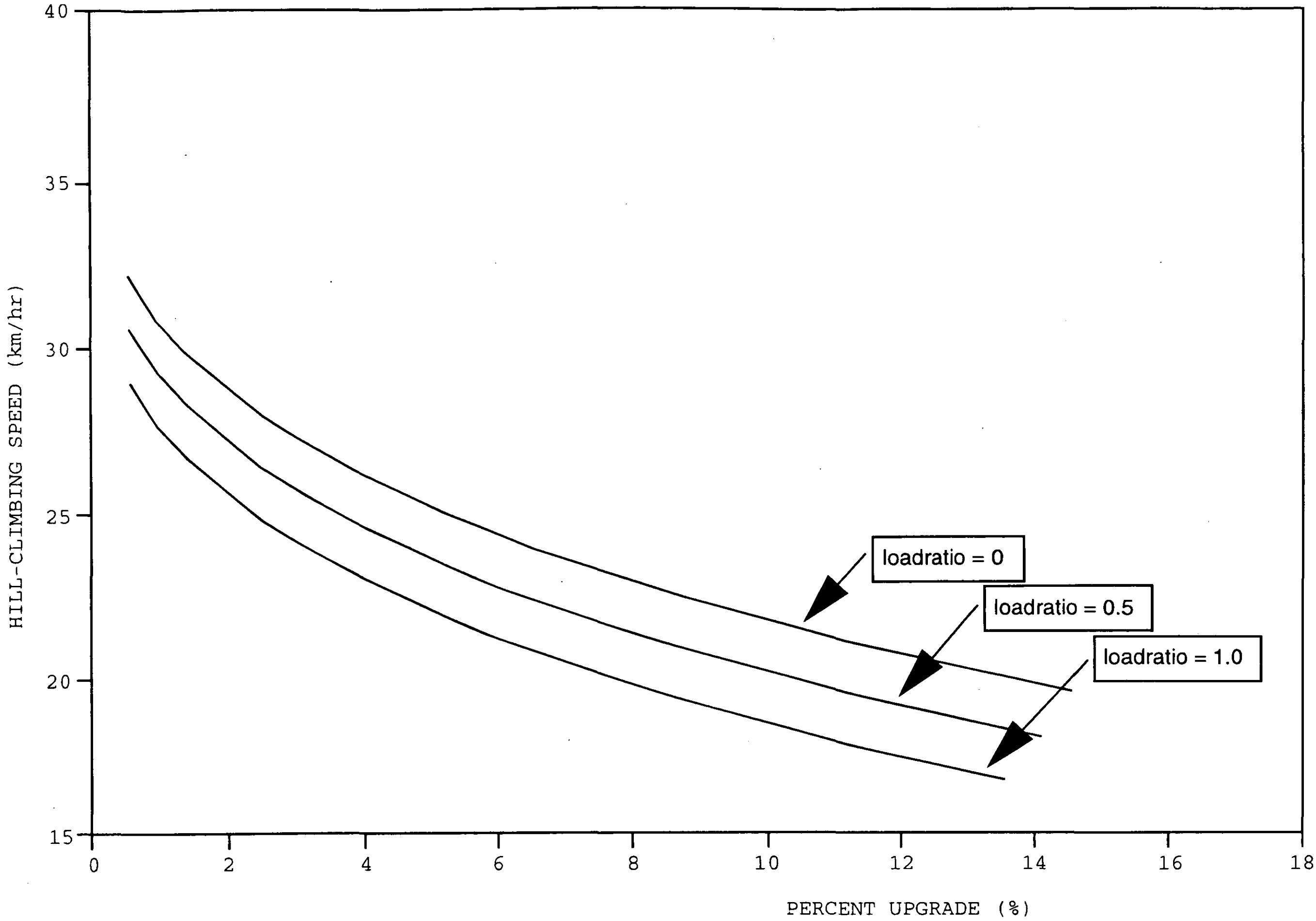

FIGURE 4 **Estimates hill-climbing speed versus upgrade.**

Models for Energy Consumption in Revenue Service

First Energy-Consumption Model

The primary purposes of the first energy consumption model were to provide input for reliable estimations of vehicle range and energy cost, and to determine systematically factors affecting the energy consumption. This model explored how bus route and operation characteristics affected the vehicle's dc energy consumption. Bus route characteristics included various street and traffic variables such as the street's longitudinal profile, number of lanes, average block length, vehicular and pedestrian volumes, number of intersections, number of stops per kilometer, density of businesses and shops, and other factors. Bus operation variables included average bus travel speed and passenger loading.

The dependent variable for the first energy-consumption model was vehicle dc energy consumption per vehicle-kilometer.

Candidates for independent variables were as follows. The four streets making up the perimeter route are very different from one another in terms of bus route and operation variables (see Table 1). Longitudinal profiles of these four streets are shown in Figure 5. The four streets collectively formed a composite independent variable. That is, this independent variable consisted of four levels, each representing one street. The variable was incorporated in the regression analysis as a set of dummy variables. Other candidate independent variables examined were load ratio, battery DOD, average vehicle travel speed, number of vehicle stops per kilometer of street, and peak and off-peak hours.

The best-fit model was:

$$Y = 0.753 + 0.169\,X_1 - 0.002\,X_2 + 1.028\,X_3 - 0.129\,X_4 - 0.618\,X_5 \qquad (4)$$

where

Y = energy consumption per kilometer of travel (kW · hr/km),
X_1 = load ratio,
X_2 = battery DOD (percent), and
X_3, X_4, X_5, and X_6 were a set of dummy variables representing Hearst Avenue, Piedmont Street, Bancroft Way, and Shuttuck Avenue, respectively; a regression analysis requires one of them to be excluded, in this case, X_6.

The t-statistics for all coefficient estimates in Equation 4 were significant at any reasonable value of α. The estimated standard error was 0.94 and the sample size was 80. R^2 was 0.98, indicating that 98

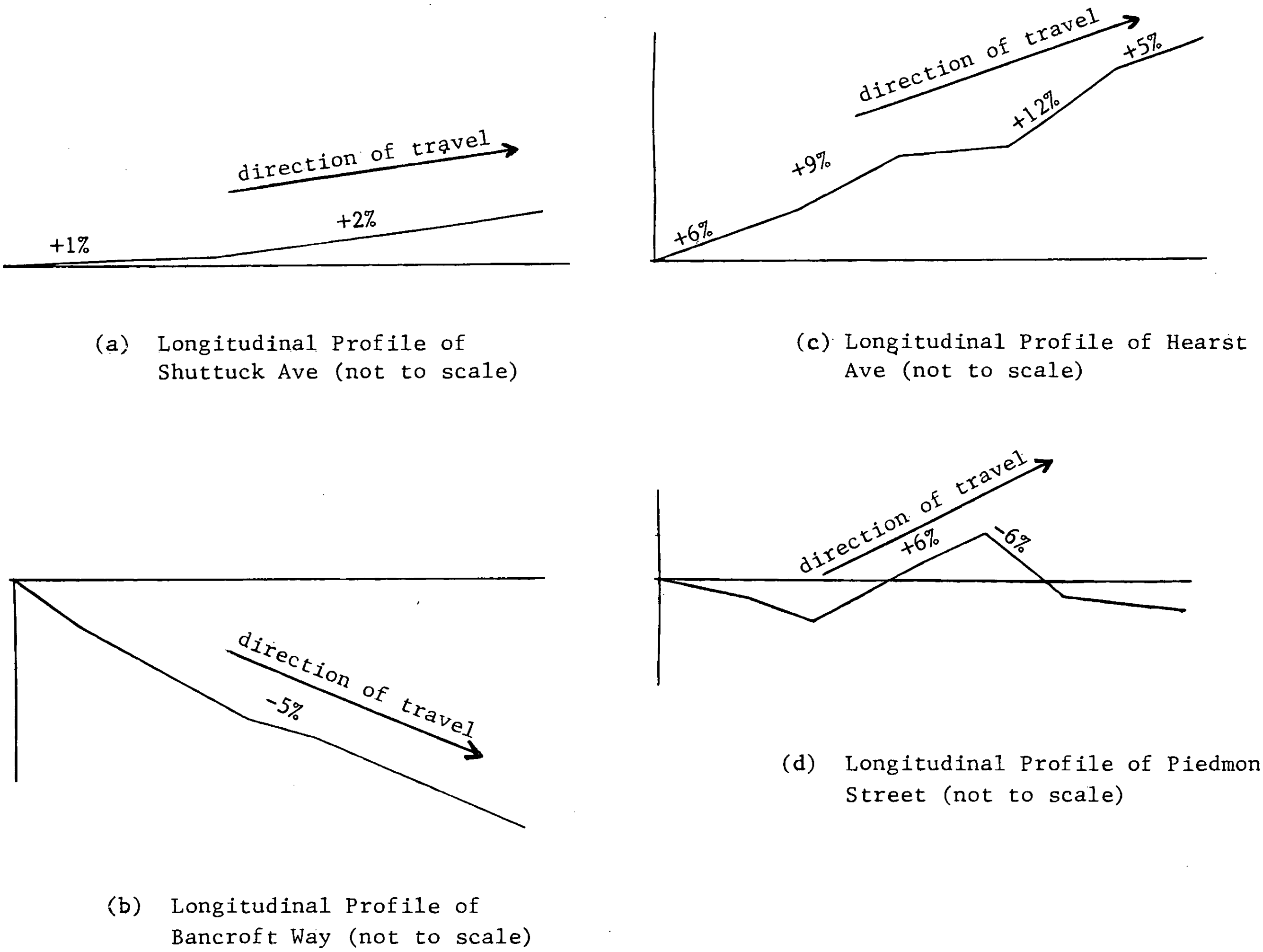

FIGURE 5 Longitudinal profile of perimeter route.

percent of total variation in the observed energy consumption per vehicle kilometer was explained by the estimated model. The other candidate independent variables were found to be nonsignificant.

Figure 6 shows estimated energy consumption per vehicle kilometer plotted against the load ratio for each of the four streets. The effects of street characteristics on the energy-consumption rate are evident in this figure. Specifically, the figure implied the following:

- Among the various street and traffic characteristics, the most dominant feature affecting the energy-consumption rate was the street's longitudinal profile (primarily the percent upgrade). This is evident in the energy-consumption rate on Hearst Avenue, which was approximately 2.4 to 2.5 times those on Shuttuck Avenue (almost flat) and Piedmont Avenue (with mild grades). Furthermore, Bancroft Way (a downhill street throughout) shows an extremely low energy-consumption rate (only 10 percent of the rate on Shuttuck).
- Other street and traffic characteristics affecting the energy-consumption rate were those collectively characterized as the degree of urbanization. Figure 6 reveals that higher degrees of urbanization slightly increased the energy-consumption rate. This is evident in the energy rate on Shuttuck (a busy main downtown street that is almost flat), which was approximately 1.2 times that on Piedmont (a small nonbusy street with mild grades).
- Passenger loading also affected the energy-consumption rate, although to a lesser extent than the street's longitudinal profile did. As expected, the energy-consumption rate increased as passenger loading increases.

The estimated energy-consumption model (Equation 4) also indicated that the battery DOD affected the energy-consumption rate. As the battery DOD increased, slightly less energy could be drawn from the battery because there was less power available. This was consistent with the earlier finding from the controlled road tests.

Second Energy-Consumption Model

Results of the first energy-consumption model strongly suggested that the street's longitudinal profile was a dominant factor influencing the energy-consumption rate. Therefore, a second energy-consumption model was developed, aimed at quantifying the effect of the longitudinal profile (namely the percent upgrade and length of upgrade) on the energy-consumption rate of the UCB electric bus in revenue service operation.

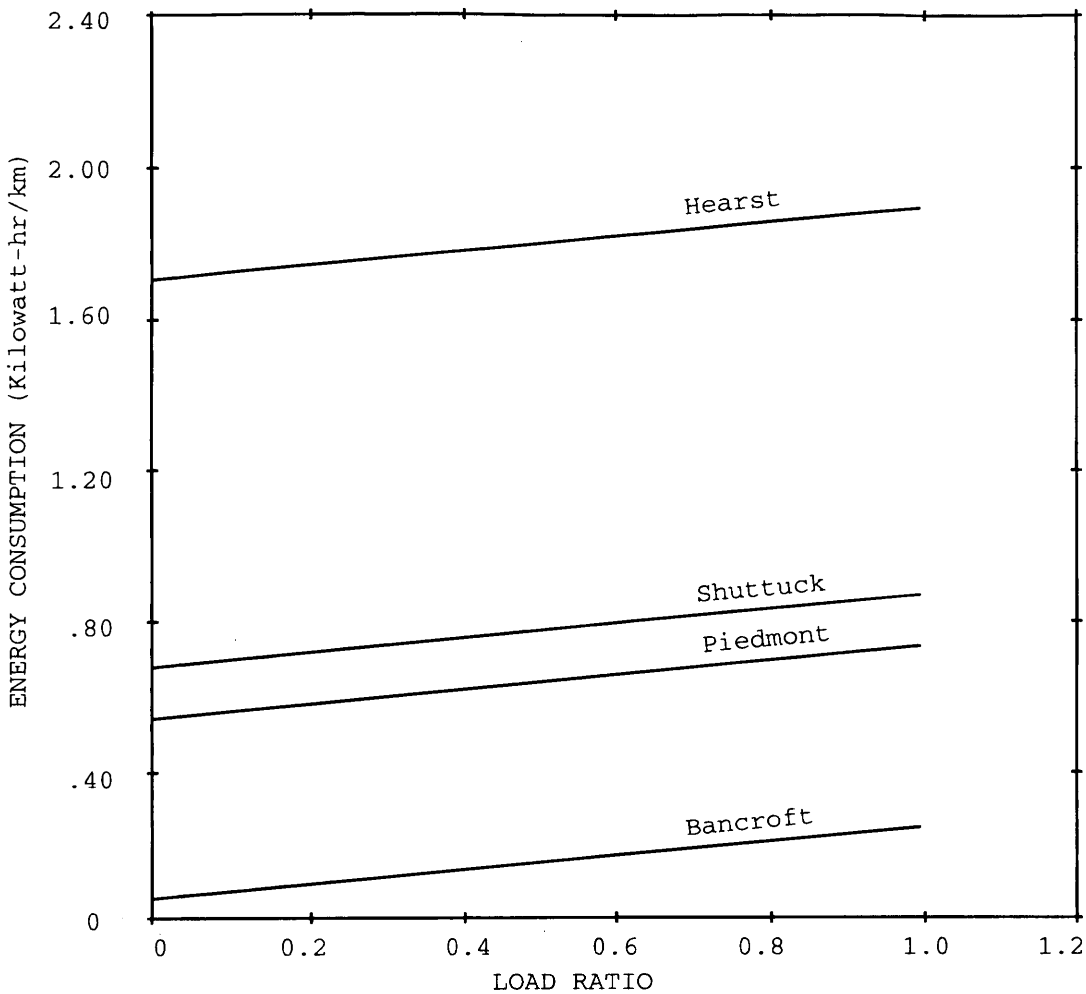

FIGURE 6 Estimated energy consumption versus load ratio for four streets.

The dependent variable in the second energy-consumption model was vehicle dc energy consumption per vehicle kilometer.

Candidate independent variables examined in the second energy-consumption model were percent roadway grade, grade length, passenger loading, and battery DOD.

The best-fit model was

$$Y = 0.139 + 0.137 \text{ (percent upgrade)} + 0.780 \text{ (load ratio)} \quad (5)$$

where Y is vehicle dc energy consumption per vehicle kilometer (kW · h/km).

R^2 was 0.62, indicating that 62 percent of total variation in the observed energy-consumption rates was explained by Equation 5. The t-statistics for the percent upgrade and load ratio were statistically significant at any reasonable value of α. The sample size was 155.

The estimated model of Equation 5 indicated that the energy consumption increased as the upgrade became steeper and the passenger loading increased, as expected. On the other hand, the grade length and battery DOD were found to be statistically nonsignificant.

Regenerative Energy

With regenerative braking, a portion of the kinetic energy in braking is returned to the battery. From the data collected in revenue service, average regenerative energy was found to be about 15 percent of vehicle dc energy consumption. This was a relatively high percentage, probably caused by the following two factors. Bus operation on Bancroft Way (a downhill street throughout) required drivers to frequently slow down and apply the brakes so that the RPM would not exceed the critical 6000. In addition, three out of the four streets were busy city streets with high vehicular and pedestrian volumes, a configuration that resulted in frequent vehicle stops and starts.

RANGE OF UCB ELECTRIC BUSES

Estimates of the range of the UCB electric buses in revenue service operation were derived from two sources: vehicle range derived from the estimated first energy-consumption model (Equation 4), and vehicle kilometers between battery change-outs, recorded daily by the drivers.

Vehicle Range Estimated from Energy-Consumption Model

The first energy-consumption model (Equation 4) was used to estimate the distance the UCB electric bus traveled before the battery reached 80 percent DOD. The estimated range values were 48 km for a load ratio of 0.5 (a half-full bus) and 44 km for a load ratio of 1.0 (a full bus).

Reported Vehicle Kilometers Between Battery Change-Outs

Drivers were asked to record vehicle kilometers between battery change-outs on a daily basis. Based on such records during the first 2 months, the distances between battery change-outs were found to be mostly between 30 and 40 km, with an average of 34 km and a standard deviation of 4 km. This average range was lower than the estimate based on the energy-consumption model. This implies that the battery packs were usually changed out before the battery DOD reached 80 percent. Most drivers were probably being conservative because they did not want to come close to running out of energy while on the road.

COMPARISON OF COSTS OF UCB ELECTRIC AND DIESEL BUSES

Capital and energy costs of the UCB electric buses and the replaced diesel buses were compared. The UCB has operated two kinds of medium-sized diesel buses. One was essentially a modified school bus and will be referred to as the UCB diesel school bus. The other was a conventional diesel bus and will be referred to as the UCB diesel transit bus. Costs for both of these UCB diesel buses are presented in comparison with costs of the UCB electric bus.

At this time, the UCB electric buses have not had sufficient mileage to allow for an estimate of their routine maintenance and repair costs.

Capital Costs

The 1993 purchase price for each UCB electric bus was $100,000. This price included the bus, three lead-acid battery packs (i.e., two spare sets per bus), and the battery change-out hardware. (The price of the three battery sets alone was $10,000.) In addition, each battery charger (one per bus) cost another $2,000. The cost of converting and wiring the bus garage to accommodate battery recharging was about $2,000 (or $500 per bus). Therefore, the total capital cost for each UCB electric bus was about $102,500.

Because both types of the UCB diesel buses were purchased many years ago, their actual purchase prices had to be adjusted to the 1993 value. This is done by using the producers price index published in the February 1993 issue of *International Financial Statistics* by the International Monetary Fund.

Total capital costs for the UCB diesel school bus, diesel transit bus, and electric bus are summarized in Table 2. The table indicates that the total capital cost of the UCB electric bus was 1.23 times that of the UCB diesel transit bus and 2.42 times that of the UCB diesel school bus. Capital costs per passenger capacity are also given in Table 2. On a per-passenger-capacity basis, the electric bus's capital cost is about 2.35 times that of the diesel transit bus and about 5.06 times that of the diesel school bus.

Energy Costs

The energy source for the UCB diesel school and transit buses is diesel fuel, and for the electric bus is the alternating current (ac) output from the wall outlet, used to recharge the lead-acid battery packs.

The electricity cost for the UBC electric bus was based on an operating policy that limits battery recharging to nighttime only. The amount of electricity (ac output) from the wall outlet was derived from the average dc energy consumption rate for the revenue service of 0.82 kW · hr/vehicle-km. The combined efficiency of the batteries and battery charger was 77 percent. Therefore, electricity from the wall outlet needed per vehicle kilometer was 1.06 kilowatt-hour. Electricity cost at night is 6 cents/kW · hr, which yielded an energy cost for the UCB electric bus of 6.4 cents/vehicle-km.

For the two types of UCB diesel buses, fuel costs were obtained from 1992–1993 fuel records.

Energy costs per vehicle kilometer and per rider for the UCB electric bus, as well as for the two types UCB diesel buses, are summarized in Table 3. The table indicates that the energy cost for the UCB electric bus was substantially lower than the costs for the two types of diesel buses. On the per-vehicle-kilometer basis, the energy cost of the UCB electric bus was about 0.49 times that of the diesel school bus, and 0.30 times that of the diesel transit bus. On a per-rider basis, the energy cost of the UCB electric bus was about 0.31 times that of the diesel school bus and 0.11 times that of the diesel transit bus.

Battery-Replacement Cost for UCB Electric Buses

For the UCB electric bus, the battery replacement cost is likely to be a significant recurring cost during the vehicle's service life. At this time, the UCB electric bus has had relatively low revenue service mileage. This makes it impossible to determine accurately

TABLE 2 Total Capital Costs for UCB Diesel and Electric Buses

	Diesel School Bus	Diesel Transit Bus	Electric Bus
1993 price	$42,340	$91,200	$102,500
Passenger capacity	46	46	22
Cost/pass. capacity	$920	$1,982	$4,659

TABLE 3 Energy Costs for UCB Diesel and Electric Buses

	Diesel School Bus	Diesel Transit Bus	Electric Bus
Cost/km (cents)	13.1	21.3	6.4
Cost/rider (cents)	3.2	9.6	1.0

the battery's service life and thus battery replacement cost. Evidence in related literature indicates that lead-acid batteries may last about 32,000 vehicle km. If so, the battery-replacement cost for the UCB electric bus will be about 31 cents/vehicle-km, or 2.5 times the combined routine maintenance and repair costs for the UCB diesel bus.

CONCLUSION

Unlike the diesel buses they replaced, the UCB electric buses are very quiet. Vehicle acceleration and braking motion is fairly smooth, comparable with the motion of the replaced diesel buses. Drivers indicate that they did not have any problem making a transition from driving diesel buses to driving the UCB electric buses. Most said that they felt comfortable driving the electric buses after the first training run.

Low speed and acceleration capabilities of the UCB electric buses on steep uphills are caused by the properties of the series-wound dc motors used. Advanced motors such as ac motors or separately excited dc motors could substantially improve these capabilities of the UCB electric buses. The capital costs and battery-replacement costs of the UCB electric bus are high. However, energy cost of the UCB electric bus is considerably lower than that of the diesel bus it replaces.

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Assessment of Alternative Structures for Privately Operated Bus Systems

JAIMU WON

Increasing concern for the mobility, environmental, and resource problems of growing or over-reliance on the automobile as a form of transport has created a strong desire for modern, efficient, and attractive public transport systems in Seoul. Practically, this generally translates into the efforts to build more subway lines. In Seoul, a total of 125 km of subway line is being constructed during the 1993–1996 period. It is expected that 300 km of subway system will be in place before 2000. This planned expansion of subway lines has placed tremendous pressures on Seoul bus transport systems, particularly bus operators. The post-subway period 2000s can be considered as a traumatic time for Seoul's bus systems. Thus, it seems obvious that alternative bus industry structures should be explored within the context of privately provided bus services. This article is concerned with various problems inherent in bus operators and characteristics surrounding bus operation in Seoul. Then it examines potential alternatives for bus industry structures, and provides advantages and disadvantages associated with each alternative.

The bus industry in Seoul is characterized by a predominance of small and independent private companies. As of 1992, a total of 90 bus companies provided intra-urban bus services. No company operated more than 150 buses, and the average fleet size was 93 vehicles. The service network totaled 349 routes, of which 74 were seat bus routes. The average round trip route length (i.e., distance from the base terminus or depot to the outer terminus) was 42.6 km. The average headway for city and seat bus was 7 min in peak period (Table 1).

The Ministry of Transportation sets fares, establishes guidelines for determining the number of buses to be licensed on each route, and regulates bus design. City or provincial governments are responsible for route planning and the licensing of bus operations.

The system is thus regulated by government, and the individual bus operators are left with little freedom to make the basic decisions that in most countries are regarded as their prerogative (subject usually to government approval), for instance to propose the services they wish to operate or the fare they will charge. Although there is a certain degree of flexibility in setting headways and frequencies, the operator is not free to decide the size of vehicle to operate or the color that it is painted.

As a result, in spite of the existence of 90 companies in Seoul, there is very little real productive competition between them. Indeed, about the only element of competition is a degree of on-the-road competition, in which routes serving the same destination but operated by different companies stop at the same stop and compete to get there first. Despite the lack of effective competition, the current structure provides few compensating gains in terms of coordination and integration. It would be difficult to achieve service improvements that would leave the existing profits of bus operators unchanged. Thus, in some respects, the Korean system combines the disadvantages of both the regulated and competitive concepts, with few of the benefits.

An average route length was 41.6 km for city bus and 46.8 km for seat bus, respectively. The route pattern is a mixture of cross city services, crossing mostly the central area of Seoul. Another feature is considerably parallel, running along the main arterial roads in the corridors. Given the radial nature of the road network and the consequent concentration of bus route as the central area is approached, it is not surprising that key passenger boarding and alighting areas are heavily congested.

One of the implications of the overlap in routes and extensive parallel running is that there are strong competitive pressures on operators to run the maximum number of buses at all times, because the share of revenue along the main corridors between operators will be determined principally by the relative number of buses. That is certainly a benefit to riders because of short headways during peak hours. In addition, the cost structure of the industry, with its low variable cost element, also encourages maximum use to be made of each bus. In a situation in which there is little external control over the frequencies at which a given number of buses are dispatched, this may lead to intentional bunching of buses at specific times perceived by the operator as representing the peak of the peak, with consequent irregular and possibly lengthy intervals between buses at other times.

It is quite common to observe the bunching of buses on major corridors leading to the city centers during peak hours. There is a long headway on routes in less populated areas. Some buses do not even stop at the bus stops, despite the fact that a couple of riders are waiting for buses.

There may also be pressure on drivers to indulge in unsafe driving practices, such as racing and queue jumping. However, it appears that the strongest incentive for drivers to speed and drive dangerously comes from inadequate running times allowed in the schedules, which almost certainly do not adequately reflect current traffic congestion levels, and delays caused by subway construction.

POTENTIAL OBJECTIVES AND ASSESSMENT

The potential objectives for the bus system, based on the current policies of government, are explored against which alternative industry structures can be evaluated. Of course, the total set of possible objectives is almost inevitably inconsistent—some will directly conflict with others. Potential objectives include

Department of Urban Engineering, Seoul City University, 8-3 Junnong-Dong, Dongdaemoon-Ku, Seoul, Korea.

TABLE 1 Bus Operating Characteristics

	Number of Routes	Number of Buses	Headway		Average Route Length(Km)	Number of Operating Frequency per Day	Operating Time per Trip(min)
			Peak	Off-peak			
City Bus*	275	6,709	7	8	41.6	8.7	124
Seat Bus**	74	1,307	7	8	46.8	8.0	115

* A city bus has a capacity of 80 passangers with 20 seats and 65 standees.

** A seat bus is a seat-only bus with a capacity of 45 seats. No standee is allowed in seat bus. An operating speed of seat bus is much higher than city bus due to the limited number of stops.

1. Provision of a comprehensive network of services to meet passenger demand,
2. Reduction of central area traffic congestion,
3. Making effective integration of the bus and subway system,
4. Providing passengers with adequate levels of comfort and safety.
5. Maintaining stability in the industry, and
6. Keeping costs and fares at a reasonable level.

Reviewing the current system with these objectives in mind, it is concluded that

1. Bus operation is financially viable.
2. Peak overloading continues to be a problem.
3. The high level of bus-to-bus transfers suggests that existing services may not closely reflect passengers' journey patterns.
4. There is a built-in reluctance to reduce service levels or abandon weak routes.
5. High capacity buses should be considered as a means of relieving overcrowding and reducing street congestion.
6. Although it is a stated objective to integrate the bus and subway systems, very little has been achieved or seems likely to be achieved under present institutions: the restructuring of routes, the provision of convenient interchange facilities, and the integration of fare systems are not likely to occur on a significant scale.
7. Efficient use of the network is hampered by the great complexity of the present route system and the limited information on the system available to the public.
8. Standards of vehicle maintenance appear high. The main safety problems relate to dangerous driving behavior of drivers and unrealistic schedules.
9. The scope under the present system for the cross-subsidization of services is very limited because of the small number of routes operated by the typical company.
10. Current policy is to discourage the formation of new companies; this limits the possibilities of introducing new techniques and management methods, and removes an incentive to existing companies to strive for improved performance.
11. Although bus planning is effectively in the hands of the city government, the resources that it devotes to this subject are very limited in terms of numbers and professional skills. There is also very little monitoring of operators' compliance with license conditions.
12. Major restructuring of the network is almost impossible with present institutions, as it would disturb the profitability of existing companies. It would be extremely difficult (*a*) to design a new route system that would leave the existing profits of individual companies unchanged and (*b*) to convince them that this would be the case so that they would agree to the changes.

ALTERNATIVE INDUSTRY STRUCTURES

Assessing the current operating practices in detail, there are seven potential alternatives:

1. Merger of companies into a small number of large private companies in each city,
2. Merger of companies into a single private company,
3. Merger of companies into a single public company,
4. A single cooperative system,
5. A district cooperative system,
6. Revenue pooling of different operators, or
7. A metropolitan transit authority.

Some of these alternatives are described further in the following sections.

Single (Large-Scale) Operator

This structure has great potential benefits in terms of coordination and integration, which is why it is so common elsewhere. If such a solution were adopted in Seoul, it would be logical for the undertakings to also own the subway systems where they exist, which implies some form of public ownership.

However, the evidence reviewed in this work suggests that merger of all urban bus companies into one organization would not improve efficiency. It should be noted that merger of all Seoul's urban bus companies would produce one of the world's largest urban bus operators. Clearly, the problems of managing the very large bus organizations that would result from such mergers would be completely beyond the experience of the current bus industry management. Therefore, in the absence of competition or a profit motivation, the single operator has a marked tendency to inefficiency, particularly if there is political intervention in day-to-day operation.

Several Large Companies

The creation of a small number of large bus companies in each city is another possibility, but this would still give rise to considerable problems of integration and coordination of services and fare, par-

ticularly with the subway system. However, this alternative would solve some of the problems inherent in the current system. Several large companies could enhance the scope for cross-subsidy. This alternative could lead to a reduction of the number of separate companies with which government agencies have to deal.

Moreover, the existence of potential competition would act as a spur to efficiency, although if each company were given a territorial monopoly (probably necessary to achieve an adequate level of cross-subsidy between routes), competition would be restricted to the supply of services (i.e., the right to operate routes instead of "on-the-road").

If a structure of a small number of large companies is to work effectively, it is important that regulating agencies are able to exercise the concept of replaceability: that is, it must be possible to replace an operator who fails to provide the required services, by transferring routes from one company to another. However, this alternative may pose a difficulty of integrating bus and subway services if the bus companies are large and powerful. There is a general lack of evidence that larger bus companies will be any more efficient than the current small companies.

Operator Cooperative

The cooperative system basically has two elements: a thorough revision of route network so as to produce a sensible and efficient route pattern, and a way of operating the fixing revised routes, by rotating them between companies, to provide an even distribution of costs and revenues. The basic principle is that the allocation of company group to route group rotates each week, so that in Week 1 Company Group A operates Route Group 1, in Week 2 Company Group A operates Route Group 2, etc. The intention is thus that every operator has the same share of the total revenue.

The cooperative system is a uniquely Korean institution that appears to work well and to be accepted by both operators and government as far as medium-sized cities are concerned. Its main disadvantage is that it involves additional dead mileage in moving buses and crews between the company's operating base and the terminus of the routes that it is operating each day. Such costs are estimated to add 1.5 to 2 percent to operating costs in a medium-sized city like Daejeon. In order to avoid this drawback, it seems necessary to provide large-scale garages as a common basis for accommodating supportive facilities and maintaining operating vehicles for all of the participating companies. Possible advantages from this common garage come from the expansion of in-house maintenance work to include major overhauls: the development of a more responsive route-planning function. City governments have been asked by bus companies to build up such facilities between the company's operating bases and the terminus of the routes.

At a more conceptual level, cooperatives also suffer from the disadvantage that they lack a competitive spur. In Daejeon, a cartel of the bus companies was formed. The cooperative has not accepted new members and has monopolized city transport. There is little incentive to innovation, particularly as far as network development is concerned. The fact that costs and revenues are shared equally also reduces the potential gains to individual companies that wish to promote change. In Gwangju, city government complained that the cooperative is not service oriented and has not done enough to discourage dirty buses or discourteous crew.

Despite these disadvantages, it is generally believed that the cooperative principle has many significant benefits that rank it above the options considered so far for overcoming the disadvantages of the present industry structure. It retains the small companies to be regarded as efficient operating units, and retains the private ownership that provides a major incentive to keep costs down. It also has the advantage of being a Korean solution that has evolved in a Korean context.

In the largest cities such as Seoul and Busan, a single cooperative would involve largely dead mileage routes; in Seoul, there are 275 city bus routes. It is therefore impractical and inefficient for all companies to rotate around all routes.

Thus, if the cooperative principle were to be applied to Seoul and Busan and other very large cities, a number of separate cooperatives would have to be created—perhaps 10 to 15 in Seoul and 4 to 5 in Busan. Ideally, each cooperative should have its own area of the city and a similar profitability profile, and it should be small enough to allow bus drivers to learn all of the routes operated. This should keep the increase in operating costs down to approximately 2 to 2.25 percent.

Revenue Pooling

It could be argued that the moving of company buses around the route under the cooperative system to equalize revenue per bus is unnecessary and wasteful. A simpler method would be a revenue-pooling system, whereby all of the revenues collected by individual companies would be deposited into a pool; this would then be shared between the companies on an agreed basis.

Revenue-pooling agreements in other countries have usually involved a fairly small number of major operators, typically two or three. Where only bus companies are involved, the revenue is usually shared on the basis of bus kilometers operated. Sometimes, however (particularly if the revenue from railways as well as buses is pooled), the revenue is shared on the basis of the percentage of revenue accruing to each company in the last year before the introduction of the pooling system. Either of these systems can work satisfactorily with a small number of operators who trust each other and in situations in which demand and the transport system are fairly static.

If the situation is changing rapidly as it is in Seoul, there will be a frequent need for adjustments to the shares of revenue that would be a cause of endless argument. In addition, the cooperative system equalizes both revenues and costs between operators, whereas a pooling system equalizes only revenues; some operators may therefore incur higher than average costs per kilometer or per bus because of the nature of their routes, and will demand a higher share of the revenue.

The current situation of the industry in Seoul does not promote mutual trust between operators; indeed, there is widespread suspicion that operators understate the revenue they receive so as to minimize tax liabilities and strengthen the case for fare increases. In these circumstances, the requirement of a revenue-pooling system in which all operators honestly report their revenues is not feasible. However, some changes in fare collection systems would provide a way of overcoming this problem. Nevertheless, the prospects for an immediate application of revenue-pooling systems are not good, and although revenue pooling in practice might evolve once cooperatives are firmly established, it is not an institutional option that can be pursued now.

Metropolitan Transit Integration Authorities

The final option considered is the formation of metropolitan transit integration authorities or MTIA. This concept is of an agency responsible for providing public transport by purchasing services

from operating companies. It would not operate any services itself, but would determine what services should be provided.

The basic division of functions between the MTIA and operating companies would be that the Authority

1. Monitors passenger demand,
2. Plans services (routes, frequencies, capacities),
3. Produces service specification (outline timetable),
4. Decides fares, and
5. Markets the services to the public.

The operating companies

1. Operate services,
2. Employ operating and maintenance staff,
3. Own assets (vehicles, depots, etc.),
4. Produce detailed timetables, vehicle, and crew duties, and
5. Supervise operations.

This distribution of functions is similar to that of the transport communities of West Germany.

In considering this structure, it is important to note that virtually all of the proposed functions of the transit integration authority—surveying demand, planning services, regulating headways, determining bus stop locations, and setting fares—are currently performed in Korea by some branch of government and not by the operators. The authority would simply bring these functions together into one body for each city.

Although there are similarities to the German model, there are several important differences. First, in Korea the transit integration authority could not be a voluntary grouping of operators, because it is highly unlikely that the large number of private companies would all voluntarily agree to changes. Thus, the authority would have to be a public institution with powers granted by legislation. Where they are in operation or under construction, subways should also be under the control of the MTIA.

A second important difference is in the area of revenue collection and distribution. If (as in Germany) the companies were responsible for collecting fares and handing over the revenue to the Authority, it is likely that not all revenue would be handed over. There would also be considerable difficulties in deciding an appropriate basis for revenue distribution. For these reasons, revenue collection would have to be entirely in the hands of the authority, ideally through abandoning the taking of cash on bus and the enhancement of the current token and ticket schemes. The authority would then reimburse the operators for running the services, either according to an agreed formula, or on the basis of prices tendered when contracts to run services were agreed.

For the MTIA to function effectively, two aspects are vital. The first is that there is close monitoring of the performance of operators so that good operators who consistently provide the specified services can be distinguished from poor performers. The second is that there should be no unwillingness to replace operators who do not perform well or who are too expensive. The principal advantage of the MTIA concept is that it breaks the link between the profitability of the individual bus operator and the routes that it operates, thereby facilitating network restructuring, bus/subway integration, and closer matching of supply to demand.

ASSESSMENT OF ALTERNATIVE STRUCTURES

To evaluate alternative industry structures, the concordance analysis was used (*1,2*). A concordance analysis is designed to select the most desirable alternatives out of a series of competing alternatives. The selection is based on a multiplicity of criteria. Each criterion is provided with a preference score, so that both quantitative and qualitative effects can be taken into account.

In an effort to establish effect matrix, 15 transport professionals and related officials were asked to provide ratings on the effects of alternative bus industry structures. They were requested to give a 100 value to the most favorable alternative and 0 value to the worst one. To establish a degree of relative importance and to provide a test of consistency in the numerical weighting to follow, the same panel members were interviewed successively to make a series of comparison. The normalized effect matrix was completed as in Table 2.

Pre-evaluation was conducted by imposing a set of constraints (in the form of threshold values or minimum acceptable level) as a basis for elimination from further consideration. Thus, 12 criteria in Table 2 become 7 in Table 3.

The next step undertaken was the elimination of less favorable alternatives. For a given vector of importance weights W, one can compute the concordance and discordance indices, IC^{ij} and ID^{ij}, for alternative O_i relative to alternative O_j.

$$IC = \begin{pmatrix} -- & IC^{12} & IC^{13} & ---- & IC^{1N} \\ IC^{21} & --- & IC^{23} & ----- & IC^{2N} \\ & & \vdots & & \\ IC^{N1} & IC^{N2} & ------- & & IC^{N,N-1} \end{pmatrix}$$

$$ID = \begin{pmatrix} -- & ID^{12} & ID^{13} & ------ & ID^{1N} \\ ID^{21} & -- & ID^{23} & ------ & ID^{2N} \\ & & \vdots & & \\ ID^{N1} & ID^{N2} & -------- & & ID^{N,N-1} \end{pmatrix}$$

The IC^{ij} and ID^{ij} can be formally defined as the concordance index, for alternative O_i with respect to O_j, and the discordance index, for alternative O_i with respect to O_j, respectively.

The next step was to establish the concordance dominance matrix F. The elements f_{ij}, $i = 1, \ldots n; j = 1, \ldots n; i \neq j$ of the concordance dominance matrix F are defined as:

$$f_{ij} = \begin{matrix} 1 \text{ if } IC^{ij} \geq \overline{IC} \\ 0 \text{ otherwise} \end{matrix} \quad \text{(threshold value)}$$

Discordance matrix G is obtained in a similar manner to F. The elements g_{ij}, $i = 1, \ldots n; j = 1, \ldots n; i \neq j$ are defined as:

$$g_{ij} = \begin{matrix} 1 \text{ if } ID^{ij} \leq \overline{ID} \\ 0 \text{ otherwise} \end{matrix} \quad \text{(threshold value)}$$

Note that in both F and G, a unit entry for the ith row and jth column indicates dominance of O_i over O_j.

Because the decision rule is to consider O_i to outrank O_j, if both $IC^{ij} \geq \overline{IC}$ and $ID^{ij} \leq \overline{ID}$ are true, then a joint dominance matrix E obtained by operation on F and G is defined. The elements e_{ij}, $1, \ldots, n; j = 1, \ldots n; i \neq j$ are defined as:

$$e_{ij} = f_{ij} \cdot g_{ij}$$

It can be observed that e_{ij} takes the value of unity only when $f_{ij} = 1$ and $g_{ij} = 1$, indicating that both conditions for dominance are met; otherwise, $e_{ij} = 0$.

TABLE 2 Evaluation of Alternative Industry Structures

Criteria \ Structure	Existing Small Companies	Several Large Companies (Private)	Single Private Bus Company	Single Public Transit Company	Single Cooperative (small City only)	Several Coopera-tive(large City only)	Revenue Pooling (many Private operators)	Metropolitan Transit Integration Authority(1)
Facilitate matching of supply to demand	0.30	0.61	0.70	0.75	0.72	0.60	0.60	0.76
Facilitate bus route rationalization/adapt-ability to change	0.10	0.61	0.70	0.80	0.75	0.60	0.30	0.81
Facilitate bus;subway integration	0.15	0.10	0.30	0.90	0.30	0.40	(2) 0.50	0.91
Permit use of high capacity buses	0.30	0.60	0.75	0.75	0.50	0.45	0.40	0.70
Allow cross-subsidiz-ation of unprofitable but socially necessary services	0.30	0.60	0.75	0.90	0.70	0.60	0.60	0.90
Permit bus;bus transfer ticketing and /or Travelcards	0.10	(3) 0.30	0.80	0.85	0.70	(3) 0.60	0.50	0.86
Permit bus;subway through ticketing and/ or Travelcards	0.05	0.20	0.40	0.90	0.60	0.40	(2) 0.40	0.90
Permit distance-related bus fares (stage/Zonal)	0.30	0.50	0.60	0.70	0.70	0.60	0.50	0.70
Ease of Implementation / acceptability to existing companies	0.50	0.45	0.10	0.40	0.42	0.60	0.10	0.40
"workability" post-implementation	0.75	0.62	0.70	0.70	0.60	0.60	0.30	0.20
Incentives to effi-ciency & innovation	0.30	(4) 0.62	0.70	0.60	0.55	0.52	0.40	(5) 0.50
Impact on cost increase	0.52	(6) 0.40	(6) 0.30	(6) 0.05	(7) 0.50	(7) 0.51	0.51	(7,8) 0.20

Note : 1. Assumes Authority works through several operator cooperatives.
2. Assumes Subway Corporation involved in pooling.
3. Assumes transfer ticketing between companies or cooperatives can be arranged.
4. Assumes concept of replaceability can be implemented.
5. Assumes competitive tendering.
6. Detrimental effect particularly in short term ; may not be so bad in longer term.
7. Assumes cooperatives can achieve some economies e.g. in joint purchasing or central workshops, but these are likely to be offset by increased 'dead' mileage.
8. Allows for costs of tendering and administration.

TABLE 3 Weighted Normalized Alternative Effect Matrix

Criteria / Alternative	C_1	C_2	C_3	C_4	C_5	C_6	C_7
O_1(Existing)	0.30	0.10	0.15	0.30	0.75	0.30	0.52
O_2(Large Private)	0.61	0.61	0.10	0.60	0.62	0.62	0.40
O_3(Single Public)	0.75	0.80	0.80	0.75	0.70	0.60	0.05
O_4(Single Coop)	0.72	0.75	0.30	0.50	0.60	0.55	0.50
O_5(District Coop)	0.60	0.60	0.40	0.45	0.68	0.52	0.51
O_6(Authority)	0.76	0.81	0.81	0.70	0.20	0.50	0.20

Through the same rating procedure as earlier, the weight vector for the reduced set of criteria was generated as follows:

C_1: Service provision	(0.08)
C_2: Route change	(0.18)
C_3: Transfer	(0.20)
C_4: High capacity	(0.07)
C_5: Workability	(0.25)
C_6: Efficiency	(0.08)
C_7: Cost	(0.14)
	Σ 1.00

Based on the weighted normalized alternative matrix, the following concordance matrix (IC) and discordance matrix (ID) were constructed.

$$IC = \begin{vmatrix} — & 0.41 & 0.62 & 0.62 & 0.62 & 0.62 \\ 0.59 & — & 0.79 & 0.61 & 0.59 & 0.54 \\ 0.39 & 0.22 & — & 0.14 & 0.14 & 0.61 \\ 0.39 & 0.40 & 0.87 & — & 0.59 & 0.54 \\ 0.39 & 0.42 & 0.87 & 0.42 & — & 0.54 \\ 0.39 & 0.47 & 0.40 & 0.47 & 0.47 & — \end{vmatrix}$$

$$ID = \begin{vmatrix} — & 0.26 & 1.00 & 0.27 & 0.18 & 1.00 \\ 1.00 & — & 0.74 & 0.22 & 0.33 & 0.76 \\ 1.00 & 0.99 & — & 0.70 & 0.67 & 0.91 \\ 0.92 & 0.28 & 0.96 & — & 0.26 & 0.73 \\ 0.70 & 0.42 & 0.98 & 0.15 & — & 0.87 \\ 1.00 & 1.00 & 0.32 & 0.72 & 0.58 & — \end{vmatrix}$$

Having completed IC and ID matrices, it is necessary to decide on threshold values. Average index (0.58) was applied in this case. The resulting concordance matrix F and discordance matrix G are then:

$$F = \begin{vmatrix} — & 1 & 0 & 0 & 0 & 0 \\ 0 & — & 0 & 0 & 0 & 0 \\ 1 & 1 & — & 1 & 1 & 0 \\ 1 & 1 & 0 & — & 0 & 0 \\ 1 & 1 & 0 & 1 & — & 0 \\ 1 & 0 & 1 & 0 & 0 & — \end{vmatrix} \quad G = \begin{vmatrix} — & 0 & 0 & 0 & 0 & 0 \\ 1 & — & 0 & 1 & 1 & 0 \\ 0 & 0 & — & 0 & 0 & 1 \\ 1 & 1 & 0 & — & 1 & 0 \\ 1 & 1 & 0 & 1 & — & 1 \\ 0 & 0 & 0 & 0 & 0 & — \end{vmatrix}$$

By confirming F and G, E is obtained.

$$E = \begin{vmatrix} — & 0 & 0 & 0 & 0 & 0 \\ 0 & — & 0 & 0 & 0 & 0 \\ 0 & 0 & — & 0 & 0 & 0 \\ 1 & 1 & 0 & — & 1 & 0 \\ 1 & 1 & 0 & 1 & — & 0 \\ 0 & 0 & 0 & 0 & 0 & — \end{vmatrix}$$

The two undominated alternatives turned out to be Alternatives 4 (single cooperative) and 5 (district cooperative). However, Alternative 5 generally received higher values on important criteria than Alternative 4. Thus, Alternative 5 was chosen as the best alternative. This outcome is generally consistent with a prior expectation, as the district cooperative has great potential benefits for a large city like Seoul in terms of revenue redistribution and route rationalization. The other reason for this outcome appears to be that district cooperative would not require much of the municipal expenditures. Although the criterion "bus and subway integration" appears rather low, the remaining criteria are more than enough to offset this criterion.

CONCLUSION

This research reveals that the idea of substantial mergers of bus companies and public ownership should be rejected. The existing companies are efficient profit-oriented units, even though some suffer from financial difficulties. However, the role that the bus industry is asked to fulfill is changing rapidly, and its weakness is in its slow adaptability under the conditions of changing passenger demands. The major issue is therefore how to devise an industry structure that preserves the best features of the current institutions while allowing for a greater level of flexibility to meet the needs of passengers.

One of the most important features of the current system is the reliance on small private companies to provide services. As suppliers of services, they appear to function well. However, from the point of view of the requirements for a network of services, the multiplicity of companies is counterproductive. Therefore, there is a strong need for much improved coordination among bus companies. This can be achieved by the formation of operator cooperative along the lines already followed in Daejeon and Gwangju cities.

The most feasible alternative turned out to be the district cooperative. The largest city, Seoul, is too large for a single cooperative and has the added dimension of subway systems. Therefore, the companies should be grouped into a number of cooperatives of between 500 and 700 buses on a district basis. This alternative leaves the basic supply side of the industry unchanged, but it opens up many possibilities for making better use of the supply of bus services through network restructuring and revenue redistribution.

REFERENCES

1. Nijkamp, P. *Multidimensional Spatial Data and Decision Analysis.* John Wiley and Sons, Inc., New York, 1979.
2. Won, J. Multicriteria Evaluation Approaches to Urban Transportation Project. *Urban Studies*, Vol. 27, No. 1, 1990.

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Bus Priority at Traffic Signals in Portland: The Powell Boulevard Pilot Project

KATHARINE M. HUNTER-ZAWORSKI, WILLIAM C. KLOOS, AND ALAN R. DANAHER

The city of Portland, Oregon, the Tri-County Metropolitan Transportation District of Oregon, and the Transportation Research Institute at Oregon State University have been involved in the Powell Boulevard Pilot Project to evaluate bus priority at traffic signals. Two priority techniques were tested in the pilot project. Green extension–early green return was tested at far-side stop locations, and queue jump was tested at a near-side stop location. In addition, two bus detection technologies were tested, which used different methods of bus detection. The pilot project involved four intersections along a 2-mi section of Southeast Powell Boulevard. Extensive traffic-impact studies were carried out before and after implementation of the bus priority technology. The project results include a summary of the equipment evaluation and the results of the traffic survey.

The city of Portland, Oregon, and the Tri-County Metropolitan Transportation District of Oregon (Tri-Met) are committed to providing excellent transit service to citizens in the Portland metropolitan area. Methods of improving transit service and performance include establishing through-transit priority, preemption at traffic signals, or both. The city and Tri-Met jointly undertook the Powell Boulevard Bus Priority Pilot Project. This project tested the effectiveness of two techniques for determining traffic signal priority for buses on Southeast (SE) Powell Boulevard in Portland. This project also evaluated two types of bus-detection technology. This pilot project is described in this paper.

PRIORITY TECHNIQUES TESTED

The two priority techniques tested in this pilot project were green extension–early green return and queue jump.

Green Extension–Early Green Return

If the signal phase serving the bus operating in a through lane approaching the intersection is already green, then the green can be extended past its normal end time. If the signal phase is red, then the green will return earlier than normal. For the Powell Boulevard test, the extensions or early returns typically ranged up to 10 sec per signal cycle in the off-peak period and up to 20 sec during peak periods. Because the overall cycle length remained the same, the added green time given to the main street was taken from the green time for the left-turn movements and the cross street. This technique was only applied when the bus had a far-side stop.

Queue Jump

A bus stopped at a red light at the stop bar will receive an advance green so that it can pull in front of the parallel stopped queue. This technique was used only at near-side bus stops with right-turn-only or bus-only lanes.

Test Locations

These two techniques were applied to four intersections along a 3.22-km section of SE Powell Boulevard between Milwaukie and 50th avenues in southeast Portland. Powell Boulevard is a major five-lane arterial road carrying 40,000 to 50,000 vehicles per day. With this heavy volume, Powell Boulevard was considered the "main street" for timing purposes. Green extension was used at three intersections (Milwaukie Avenue, 39th Avenue, and 50th Avenue), whereas queue jump was used only at only one intersection (26th Avenue). All four locations are controlled by Type 170 controllers with Wapiti IKS actuated firmware.

BUS DETECTION TECHNOLOGY TESTED

The city of Tri-Met also evaluated two bus detection technologies in this pilot project, designated System A and System B, which used different methods of bus detection. System A used radio frequency (RF) activated tags on the bus with special RF readers installed along the roadside. System B used a special transmitter on the bus that was read through standard vehicle loop detectors imbedded in the pavement. Tables 1 and 2 identify the basic characteristics of the two systems. For the pilot project, 75 buses operating on the Tri-Met Powell Number 9 Line were outfitted with both System A tags and System B transmitters.

GREEN EXTENSION OPERATION DESCRIPTION

Because the green extension–early return technique was applied to the Powell Number 9 Line buses using SE Powell Boulevard, the bus through movement was associated with the main-through coordinated phase. The result was that this bus priority technique generally added green time for the major traffic movement on SE Powell Boulevard.

K. M. Hunter-Zaworski, Transportation Research Institute, Merryfield Hall 100, Oregon State University, Corvallis, Oreg. 97331-4304. W. C. Kloos, Signal System Manager, City of Portland, Oreg. A. R. Danaher, Project Development Coordinator, Tri-Met, Portland, Oreg.
Current address of W. C. Kloos and A. R. Danaher: Kittelson and Associates, Inc., Transportation Planning/Traffic Engineering, 610 SW Alder, Suite 700, Portland, Oreg. 97205

TABLE 1 System A Description

General Description	Radio frequency activated tags on the buses with special RF readers installed along the wayside. Includes a master unit for interfacing with traffic controller and logging reader data.
Vehicle Tag/Transmitter	
Type	RF tag 236mmL x 61mmW x 19mmH
Equipment Cost per Bus	$40
Mounting Method	Tag is mounted on the outside front of the bus above the reader board. No power supply is required.
Wayside Cost per Intersection*	$29,000 (Hardware) $2,000 (labor)
Interface with traffic controller	The master System A controller receives info from all readers. System A controller provides 6.25 Hz priority call to traffic controller.
Data Logging Capabilities	The master should store data for up to 7,000 buses. Data includes time arrived, time departed, active phases at preempt call, and start / stop times of priority phase "green".

The two System A intersections had an advance RF tag reader about 122 to 183 m before the intersection. These readers were mounted on existing street lighting and signal poles in the street right-of-way. As a tagged bus passed the reader, the bus's identification number was passed to the System A controller, which activated a "bus priority call" to the traffic controller. The System A controller continued the call until the bus passed a checkout reader attached to the near-side traffic signal pole. The System A controller has a "max" timer to terminate excessively long bus priority calls should a checkout reader fail. The System A controller logged the in and out times for every bus. The System A controller also logged the "start and end of main street green" for every cycle with preemption at that intersection.

At the System B intersection an advance inductive loop was located in the curb lane for each direction. A receiver for System B was located in a remote amplifier cabinet near the loop. The receiver recognized buses with "legal" transmitters and passed a call on to the Type 170 controller City staff constructed an external logic package to receive the System B call and convert it to a call for bus priority to the controller. A second inductive loop with a receiver

TABLE 2 System B Description

General Description	Special transmitter on bus that transmits ID code that is read through a standard vehicle loop imbedded in the pavement. A detector reads the ID code and also acts as standard loop detector amplifier.
Vehicle Tag/Transmitter	
Type	Transmitter 114.3 mm diameter x 19mmH
Equipment Cost per Bus	$75
Mounting Method	Transmitter is mounted under bus 0.6 m behind front bumper. Transmitter requires power source
Wayside Cost per Intersection*	$15,000 (hardware) $3,500 (labor, inc. new loops)
Interface with traffic controller	Individual detectors tied to City external logic package. Logic package provides 6.25 Hz priority call to traffic controller.
Data Logging Capabilities	Each detector unit should store approx. 9,000 bus observations. Data must be retrieved from each Model 630.

* approximate cost for a typical intersection with "green extension" on two approaches (based on prices of equipment purchased for this pilot)

was located at the near-side stop bar to check out the bus. The city's external logic package also had a max timer that terminated the bus priority call should a checkout call be missed.

QUEUE JUMP OPERATION DESCRIPTION

The single queue jump test was conducted at 26th Avenue for eastbound (EB) buses. A single 6-m-long presence loop was cut into the existing near-side EB bus stop lane. This lane was designated Right Turn Only Except Buses. A receiver was installed in a remote amplifier cabinet near the loop. A properly detected bus caused system B to give the controller a call for the exclusive queue jump phase. If a bus was at the bus stop during a normal EB through red phase, the bus received a short advance green as displayed on a programmed visibility signal head, which was only visible to vehicles in the right-turn and bus-stop lane. This advance green occurred at the normal start of EB through green. The bus was then able to pull in front of the EB through queued traffic.

PILOT PROJECT RESULTS

Impact of Signal Priority on Traffic

Extensive field data were collected to evaluate the effectiveness of the bus priority techniques used in this project. Traffic studies undertaken simultaneously included turning movement counts and approach-vehicle delay measurements at the intersections of Milwaukie, 26th, 39th, and 50th with SE Powell Boulevard, plus bus travel time and delay, vehicle occupancy counts, and bus passenger counts for this corridor. Data were also collected for bus routes crossing SE Powell Boulevard. Data were collected for 3 days before and after the implementation of the priority operation, during three time periods each day: 7:00 a.m. to 9:00 a.m., 11:30 a.m. to 1:30 p.m., and 4:00 p.m. to 6:00 a.m. The logging abilities of the bus detection equipment also allowed a continuous accumulation of bus travel time information. The Oregon State University Transportation Research Institute analyzed the data from the field studies. The goal of the field data collection was to determine the following:

1. Reduction in bus travel time for Number 9 Line on SE Powell Blvd;
2. Effect on the length of delay to other vehicles; and
3. Total decrease (or increase) in person delay to people at these intersections.

Unfortunately, the before and after traffic surveys provided somewhat inconclusive data about the impact of bus signal priority on traffic conditions because of three factors:

1. Turnover in survey personnel led to some inconsistencies in the data collection procedures;
2. Two accidents during the a.m. peak period of the after study limited the sample size during this period; and
3. The signal operation at 26th Avenue was not optimally timed for the queue jump operation, resulting in reduced green time for the westbound (WB)-through movement.

Data Collection

A major problem with the experimental aspects of the pilot project included a 3-week time lapse between the before and after studies. This delay way caused by a city road crew grinding up one of the loop detectors at the intersection of 39th Avenue and SE Powell Boulevard. As a result of the delay, there was a significant turnover in data collection personnel. The training of the data collectors was inconsistent, and as a result, data sheets often were not filled in correctly or had a number of missed readings. In some instances there were significant gaps in the data because of late arrivals of data collectors. The large gaps in the before data were filled in with data collected at a later time. The types of data with the most problems were the tally of the number of nonstopped vehicles and the readings of queue length and number of stopped vehicles.

There were also a number of problems with the bus travel time data, including delays associated with driver changeovers, disruptive passengers, wheelchair boardings, and large numbers of passengers boarding at major transfer stops.

However, the following can be reported:

- Bus travel time—Figure 1 presents the comparison of the total corridor bus travel times for Powell Number 9 Line during weekday peak periods, based on the bus check-in and checkout times logged by the bus detection equipment. Generally the bus travel times decreased in the peak period in the peak direction (5.0 percent decrease for inbound in the a.m. and 7.8 percent decrease for outbound in the p.m.). Part of the reason for increased WB travel time during the p.m. peak can be attributed to the signal timing problems that occurred at the queue jump intersection (26th Avenue). The method used to provide the EB queue jump resulted in a higher traffic delay for SE Powell Boulevard through traffic, especially WB. The city has analyzed the potential causes and is developing an improved method for providing queue jump operation, which is expected to reduce the impact on through traffic.
- Delay to other vehicles—No clear pattern developed from the delay studies at the four intersections studied. Overall there was no substantial change in total vehicle delay.
- Total bus passenger delay—Figure 2 indicates that the computed person delay for bus passengers on the Powell Number 9 Line decreased 12.3 percent with bus priority.
- Total person delay—Figure 3 indicates that the overall total intersection person delay (both bus and automobile modes) did not significantly change in the peak periods, although the delay did increase slightly during the off-peak period.

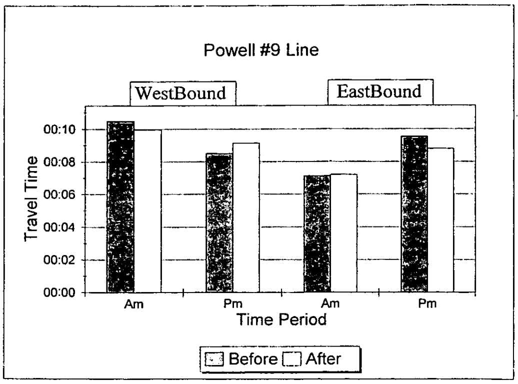

FIGURE 1 Bus average travel time.

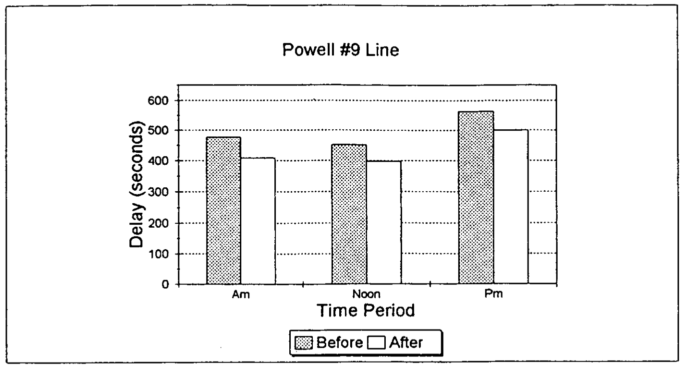

FIGURE 2 Bus passenger delay.

Equipment Performance

The equipment performance for Systems A and B is summarized in Tables 3 and 4.

System A

This pilot project was actually an equipment development project for System A. As with any development project, problems occurred. One of the biggest problems was that no written equipment specifications were prepared. Because of this lack, there were some misunderstandings about equipment design and expectations. Some of the more difficult problems occurred with the user interface, which did not allow the user to view the current master settings. Also, difficulty in communicating between the master and the personal computer led to lost data.

System B

The System B detectors worked simply and reliably, and city of Portland maintenance staff found the units easy to understand and well built. During the project, System B equipment supplied more sensitive "high gain" units, which improved the overall bus recognition accuracy. One problem with System B is that it does not provide a complete system for providing priority. An individual detector is installed at each loop, and the end user needs to provide the necessary external logic package to provide the priority call.

CONCLUSIONS

Impact of Signal Priority on Traffic

As noted above, the before and after traffic surveys provided inconclusive data about the impact of bus signal priority on traffic conditions. However, two conclusions can be drawn:

1. Bus travel time for the Powell Number 9 Line was reduced slightly in the peak direction of travel during peak periods with the bus signal priority; and
2. Bus passenger delay for the Powell Number 9 Line was reduced with the bus signal priority.

It should be realized that the test corridor on SE Powell Boulevard was only 2 mi long. Thus, the total bus travel time savings realized from signal priority might not be expected to be significant.

From a traffic survey perspective, it is important that there be more consistency in survey personnel and methods. In future projects the city and Tri-Met will look for streamlined survey procedures to obtain more reliable before and after data, possibly including some automation of the vehicle delay estimation process.

Equipment Performance

System A

Overall the results on this pilot project were mixed. System A is a complex design with several components (readers, reader inter-

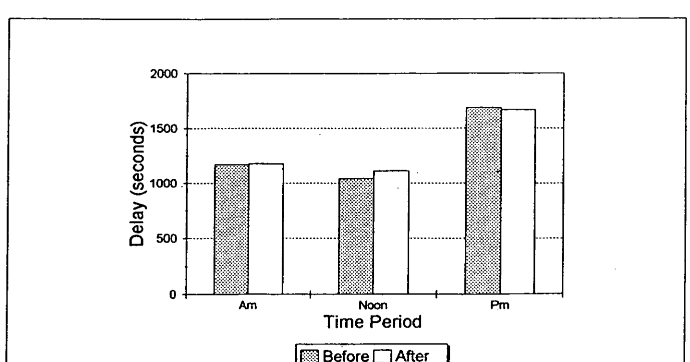

FIGURE 3 Total intersection person delay for all four intersections.

TABLE 3 Equipment Performance Evaluation—System A

Detection Location Issues	Generally limited to existing pole locations, unless willing to install new poles. May constrain getting desired detection point.
Ease of Installation	Used existing poles for antennas and readers. Required power and comm. cable from controller to readers. Requires fine tuning of antenna orientation.
Bus Reading Accuracy	Generally 96% to 99%.
Equipment/System Reliability	Overall poor performance on this pilot project. The equipment was still under development during our testing. Various errors occurred with all components.
Data Logging Issues	The System A master did not have specified capacity. Often staff were unable to retrieve data (Some records were lost).
User Interface	Generally easy to use. Unable to view the existing settings in an operating master.

TABLE 4 Equipment Performance Evaluation—System B

Detection Location Issues	Must make sure that the loop is in bus travel lane (may be problem where bus tends to use more than one specific lane). No easy way to "fine tune" loop location.
Ease of Installation	Generally will require installation of new vehicle loops at proper locations. Requires power and comm. cable for remote amplifier. Overall installation like standard vehicle detector.
Bus Reading Accuracy	Generally 97% to 99%, although had 90% to 95% with larger loops (i.e. 6x17).
Equipment/System Reliability	The Model 630 detectors worked reliably during the test period.
Data Logging Issues	The Model 630s appeared to properly record the bus data. Since there is no central master, the data had to be retrieved from each individual 630 (i.e. 4 different places at 39th).
User Interface	Intuitive interface that was easily mastered by staff. Issue of needing to verify PC time before connecting to the 630.

faces, and master). This complexity can lead to additional operation and maintenance problems. However, the contractors for System A have assured Tri-Met and the city of Portland that they will rectify the problems discovered on this project and provide upgraded equipment for further testing on SE Powell Boulevard. Assuming that this added testing is successful, System A could be considered for further installations in the Portland region.

System B

The System B detectors worked well on this pilot project. The city and Tri-Met will be considering this system for future installations in Portland.

FUTURE DIRECTIONS

The city of Portland and Tri-Met will continue other pilot projects in the bus priority field. This fall the city and Tri-Met will begin a pilot test of System C for the detection equipment. Future tests will also evaluate optimizing the traffic operations techniques used in this project.

Overall this project has helped city of Portland and Tri-Met staff to cultivate a strong, supportive relationship, which is required if bus priority is to become a reality.

ACKNOWLEDGMENTS

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Transit Vehicle-Type Scheduling Problem

AVISHAI CEDER

This work addressed the problem of how to allocate vehicles efficiently for carrying out all of the trips in a given transit timetable, in which each vehicle is assigned a chain of trips, some of which may be deadhead (empty) trips. The methodology presented takes into account the association between the characteristics of each trip (urban, peripheral, intercity, etc.) and its required vehicle type. The problem is based on given sets of trips and vehicle types, in which the categories are arranged in decreasing order of vehicle cost. Therefore, each trip can be carried out by its vehicle type, or by other types listed in priority order. This problem can be formularized as a cost-flow network problem with a nonpolynomial-hard complexity level. Thus, a heuristic algorithm was developed in this work on the basis of the deficit function theory. A real-life example is presented at the end of the paper to assess the methodology's effectiveness.

The transit scheduling process in general comprises three main components. First, the timetables are established based on passenger demand. Second, chains of trips are created; each is associated with one vehicle. Third, the driver duties are constructed (crew scheduling), based on various constraints and work rules. The component dealt with in this study is how to allocate vehicles efficiently for carrying out all of the trips in a given timetable, in which each vehicle is assigned a chain of trips, some of which may be deadhead (DH) (empty) trips.

In the vehicle scheduling component, the major objective is to minimize the cost of the vehicle assignment task. This usually coincides with minimizing the number of vehicles required to carry out all of the timetables, provided that the cost of the DH trips is less than the cost involved in employing additional vehicles. Several procedures and techniques are reported in the literature for handling the vehicle scheduling component efficiently (not entirely optimally because of the complexity of the problem). Most of the reported studies, as well as the procedures commonly carried out by practitioners, consider one type of transit vehicle. However, because of recently proposed and implemented deregulation and privatization strategies, more than one type of vehicle is being used in operation (e.g., minibuses, articulated and double-decker buses, and standard buses with varying degrees of comfort and different number of seats).

It is the purpose of this study to address the vehicle scheduling problem while taking into account the association between the characteristics of each trip (urban, peripheral, intercity, etc.) and its required vehicle type. This is to comply with a certain level of service required by each trip in terms of comfort, seat availability, and other operational features.

This work comprises seven sections. Section 1 is the introduction. Section 2 provides the background on the deficit function methodology that is used extensively in the proposed solution. Section 3 interprets the problem as an optimization problem. Section 4 provides the various definitions used. Section 5 describes the algorithm developed. Section 6 presents a real-life example, and Section 7 contains some concluding remarks.

Civil Engineering Department, Technion-Israel Institute of Technology, Transportation Research Institute, Haifa 32000, Israel.

BACKGROUND OF DEFICIT FUNCTION

Following is a description of the deficit function approach for assigning the minimum number of vehicles to allocate for a given timetable. A deficit function is simply a step function that increases by one at the time of each trip departure and decreases by one at the time of each trip arrival. Such a function may be constructed for each terminal in a multiterminal bus system. To construct a set of deficit functions, the only information needed is a timetable of required trips. The main advantage of the deficit function is its visual nature. Let $d(k, t, S)$ denote the deficit function for terminal k at time t for the schedule S. The value of $d(k, t, S)$ represents the total number of departures minus the total number of trip arrivals at terminal k, up to and including time t. The maximal value of $d(k, t, S)$ over the schedule horizon $[T_1, T_2]$ is designated $D(k, S)$.

Let t_s^i and t_e^i denote the start and end times of trip i, $i \in S$. It is possible to partition the schedule horizon of $d(k, t, S)$ into a sequence of alternating hollow and maximal intervals. The maximal intervals $[s_i^k, e_i^k]$, $i = 1, \ldots n(k)$ define the interval of time over which $d(k,t)$ takes on its maximum value. Note that the S will be deleted when it is clear which underlying schedule is being considered. Index i represents the ith maximal intervals from the left, and $n(k)$ represents the total number of maximal intervals in $d(k, t)$. A hollow interval is defined as the interval between two maximal intervals. Hollows may consist of only one point, and if this case is not on the schedule horizon boundaries (T_1 or T_2), the graphical representation of $d(k, t)$ is emphasized by a clear dot.

If the set of all terminals is denoted as T, the sum of $D(k)\ \forall\ k \in T$ is equal to the minimum number of vehicles required to service the set T. This is known as the fleet size formula. Mathematically, for a given fixed schedule S:

$$N = \sum_{k \in T} d(k) = \sum_{k \in T} \max_{t \in [T_1, T_2]} d(k, t) \tag{1}$$

where N is the minimum number of buses to service the set T.

When DH trips are allowed, the fleet size may be reduced below the level described in Equation 1. Ceder and Stern (*1*) describe a procedure based on the construction of a unit reduction DH chain (URDHC), which, when inserted into the schedule, allows a unit reduction in the fleet size. The procedure continues inserting URDHCs until no more can be included, or a lower boundary on the minimum fleet is reached. The lower boundary is determined from the overall deficit function defined as $g(t, S)_{k \in T} = \Sigma d(k, t, S)$. This function represents the number of trips simultaneously in operation.

Initially, the lower bound was determined to be the maximum number of trips in a given timetable that are in simultaneous oper-

ation over the schedule horizon. Stern and Ceder (*2*) improved this lower bound, based on the construction of a temporary timetable in which each trip's arrival time is extended to the time of the first trip that may feasibly follow it in *S*.

The deficit function theory was extended by Ceder and Stern (*3*) to include possible shifting in departure times within bounded tolerances. Basically, the shifting criteria is based on a defined tolerance time $[t_s^i - \Delta_a^i, t_s^i + \Delta_d^i]$, where Δ_a^i is the maximum advance of the trip scheduled departure time (early departure), and Δ_d^i is the maximum delay allowed (late departure). The maximum interval is then compared with the appropriate tolerance time elements for establishing conditions in which it is possible to reduce the fleet size by one via certain shifts.

The algorithms of the deficit function theory are described in detail by Ceder and Stern (*1,3*). However, it is worth mentioning the next terminal (NT) selection rule and the URDHC routines. The selection of the NT in attempting to reduce its maximal deficit function may rely on the basis of garage capacity violation, or on a terminal whose first hollow is the longest. The rationale here is to try to open up the greatest opportunity for the insertion of the DH trip.

Once a terminal k is selected, the algorithm searches to reduce $D(k)$ by shifting departure times (if allowed). Then all of the $d(k, t)$ values are updated and the NT rule is again applied. When no more shiftings are possible, the algorithm searches for a URDHC from the selected terminal while considering possible blending between DH insertion and shiftings in departure times. In the URDHC routines there are four rules: $R = 0$ for inserting the DH trip manually in a conversational mode, $R = 1$ for inserting the candidate DH trip that has the minimum travel time, $R = 2$ for inserting a candidate DH trip whose hollow starts farthest to the right, and $R = 3$ for inserting a candidate DH trip whose hollow ends farthest to the right. In the automatic mode ($R = 1, 2, 3$), if a DH trip cannot be inserted and the completion of a URDHC is blocked, the algorithm backs up to a DH candidate list and selects the next DH candidate on that list.

In the fixed schedule problem, the algorithm also terminates when the improved lower bound (*3*) is equal to $D(S)$. In the variable schedule problem (when shiftings are allowed), the algorithm also uses this comparison, and if the improved lower bound is equal to $D(S)$, the URDHC procedure (with shiftings) ceases and the shifting-only mode is applied. If the latter results in reducing $D(S)$, the URDHC procedure is again activated. The process terminates when $D(S)$ cannot be further reduced.

Finally, all of the trips, including those that were shifted and the DH trips, are chained together for constructing the vehicle schedules (blocks). Two rules can be applied for creating the chains: first in-first out (FIFO), and a chain-extraction procedure described by Gertsbach and Gurevich (*4*). The FIFO rule simply links the arrival time of a trip to the nearest departure time of another trip (at the same location), and continues to create a schedule until no connection can be made. The trips considered are deleted and the process continues. The chain-extraction procedure allows an arrival-departure connection for any pair within a given hollow (on each deficit function). The pairs considered are deleted and the procedure continues. Both methods end with the minimum derived number of vehicles (chains).

OPTIMIZATION FRAMEWORK

The problem is based on given sets *S* of trips and *M* of vehicle types. The set *M* is arranged in decreasing order of vehicle cost so that if $u \epsilon M$ is listed above $v \epsilon M$, it means that $c_u > c_v$, where c_u, c_v are the costs involved in employing vehicle of type m and n, respectively. Each trip $i \epsilon S$ can be carried out by vehicle type $u \epsilon M$ or by other types listed before u in the above-mentioned order of M.

The problem can be formularized as a cost-flow network problem, in which each trip is a node, and there is an arc connecting between two trips if, and only if, it is possible to link them in time sequence with and without DH connections. On each arc (i, j), there is a capacity of one unit and an assigned cost C_{ij}. If the cost of the lower-level vehicle type associated with trip i is higher than the cost of the vehicle type (lower level possible) required for trip j, then $C_{ij} = c_i$. That is, $C_{ij} = max\ (c_i, c_j)$. The use of such formulation was implemented by Costa et al. (*5*), while employing three categories of solutions: (a) a multicommodity network flow, (b) a multidepot vehicle scheduling problem, and (c) a set partitioning problem with side constraints. The mixed-integer programming of these problems is known as nonpolynomial-hard (NP-hard): as, for example, in Bertossi et al. (*6*).

Because of the complexity involved in reaching an optimal solution for a large number of elements (trips) in *S*, a heuristic method has been realized as a more practical approach. This article develops a heuristic procedure based on the deficit function theory for transit vehicle scheduling.

The heuristic algorithm developed in this article is titled the vehicle-type scheduling problem (VTSP) algorithm. It begins by establishing lower and upper bounds on the fleet size. The upper bound is attained by creating different deficit functions, each associated with a certain vehicle type $u \epsilon M$, in which it includes only the trips whose lower-level required vehicle type is u. Certainly, this scheduling solution reflects high cost, caused by the large number of vehicles demanded. The lower bound on the fleet size is attained by using only one vehicle type: the most luxurious one with the highest cost that can clearly carry out any trip in the timetables. In addition, for the lower-bound case, the cost required is high. Between these bounds on fleet size, the procedure searches for the best solution based on the properties and characteristics of the deficit function theory.

This optimization framework is presented in Figure 1, with (C_1, N_1) and (C_2, N_2) representing the lower- and upper-boundary solutions, respectively. Following are the definitions of the VSTP algorithm that are based mainly on the definitions of the deficit function theory.

DEFINITIONS

- S = the set of required trips in the fixed trip schedule;
- T = the set of all terminals (or start and end points) in the trip schedule;
- M = the set of all vehicle types;
- $\{'kq('kq)\}$ = the matrix of DH trip times from terminal k to q and its associated possible service trip times (in parentheses);
- $[T_1, T_2]$ = the span of the schedule horizon;
- $d(k, t, S)$ = the deficit function for terminal k, at time t, for the schedule S;
- $D(k, S) = \max_t d(k, t, S)$ = the maximum deficit over all $t \epsilon [T_1, T_2]$ at terminal k, for schedule S;
- $D(S) = \Sigma_{k \epsilon T} D(k, S)$ = the total deficit;
- $[s_i^k, e_i^k]$ = start and end time, respectively, of the ith max interval of the deficit function for terminal k, i = 1, 2, . . . $n(k)$;

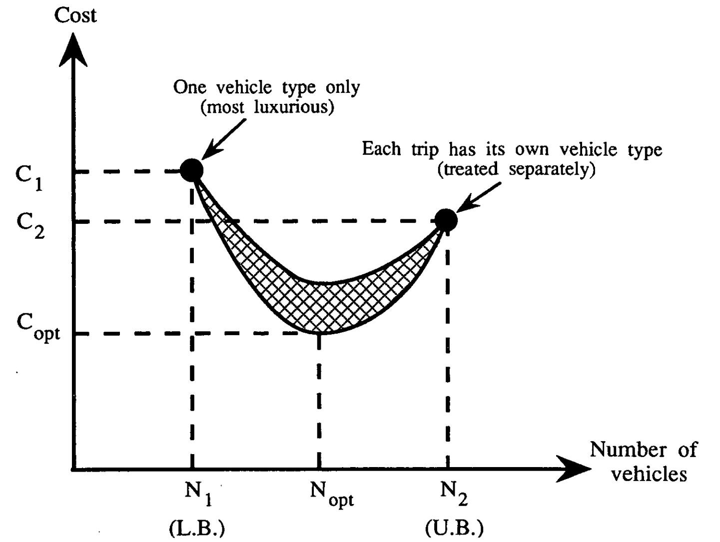

FIGURE 1 Trade-off situation between total cost and total number of vehicles.

$[e_i^k, s_i^k + 1]$ = end and start times, respectively, of the ith hollow of the deficit function for terminal k, $i = 0, 1, 2, \ldots n(k)$;

URDHC = abbreviation for unit reduction deadhead chain; that is, a chain of DH trips that reduces by one $D(k, s)$ for a given $k \epsilon T$;

t_{su}^i = start time of trip $i \epsilon S$ of type $u \epsilon M$;

t_{eu}^1 = end time of trip $i \epsilon S$ of type $u \epsilon M$;

Δ_{du}^1 = maximum allowed delay from the scheduled departure time of trip $i \epsilon S$ of type $u \epsilon M$;

Δ_{au}^i = maximum allowed advance of the trip scheduled departure time of trip $i \epsilon S$ of type $u \epsilon M$;

$d_u(k, t, S)$, $D_u(k, S)$, $D_u(S)$, $[s_{iu}^k, e_{iu}^k]$, $[e_{iu}^k, s_{(i+1)u}]$ refer to these definitions with respect only to trips of type $u \epsilon M$;

C_u = the cost involved in employing vehicle of type $u \epsilon M$;

N_1 = the minimum number of vehicles required to service all trips in S for a single vehicle type;

N_{2u} = the minimum number of vehicles required to service all trips of type $u \epsilon M$ in S;

$N_2 = \Sigma_{u=1} N_{2u}$ = the sum of all minimum numbers of vehicles required when treating each type separately;

$C_1 = N_1 c_1$ = the total cost involved in employing N_1 vehicles of type 1 (most luxurious);

$C_2 = \Sigma_{u=1} N_{2u} c_u$ = the total cost involved in employing N_2 vehicles (for each type separately);

C = the objective function of minimal total cost required to service all of the trips in S while complying with the vehicle type constraints.

VTSP ALGORITHM

The VTSP algorithm developed is heuristic in nature while incorporating all of the components of the deficit function methodology. Because of the graphical features associated with the deficit function theory, the algorithm can be applied in an interactive manner or in an automatic mode, along with the possibility to examine its intermediate steps.

The following is a general description of the VTSP algorithm in a stepwise manner.

Step 0 Arrange the set of vehicle types M in decreasing order of vehicle cost (so that if $m \epsilon M$ is listed above $n \epsilon M$, it means $c_m > c_n$).

Step 1 Solve the problem as a single vehicle type problem using the deficit function theory, including the DH and shifting procedures (*1,2,3*), to obtain N_1 vehicles considered as type 1 with a total cost of C_1, where $C_1 = N_1 c_1$.

Step 2 Partition the trips by their associated type and apply the deficit function methodology with the DH and shifting procedures (*1,2,3*), for each type separately. Sum the number of vehicles derived to obtain a total of N_2 vehicles with a total cost, where $C_2 = \sum_{u=1} N_{2u} c_u$ and $N_2 = \sum_{u=1} N_{2u}$.

Step 3 If $N_1 = N_2$, STOP. Use the solution of Step 2.

Step 4 Consider $d_u(k, t)$ as in Step 2 for all $k \epsilon T$ and $u \epsilon M$.

Step 5 Perform the shifting-only procedures for shifting departure times within their tolerances (*3*).

Step 6 Find a URDHC (*1,2,3*), such that a DH trip (with possible shiftings) can link between trip i of type u and trip j of type v if and only if one or more of the following conditions are fulfilled: (a) $u < V$; (b) the URDHC aims at saving a vehicle of type w and $w < v$; or (c) the URDHC aims at saving a vehicle of type w and $c_v - (c_w + c_u) < 0$. If no URDHC can be found, stop.

Step 7 Examine whether the total cost of the URDHC (DH cost) is less than the cost of saving one vehicle (of the type considered). If not, delete this possibility and go to Step 6. Otherwise, update $d_u(k,t)$ for all $k \epsilon T$ and $u \epsilon M$.

Step 8 Apply the improved lower-bound check (*2*). If it equals to $D(S)$, go to Step 5.

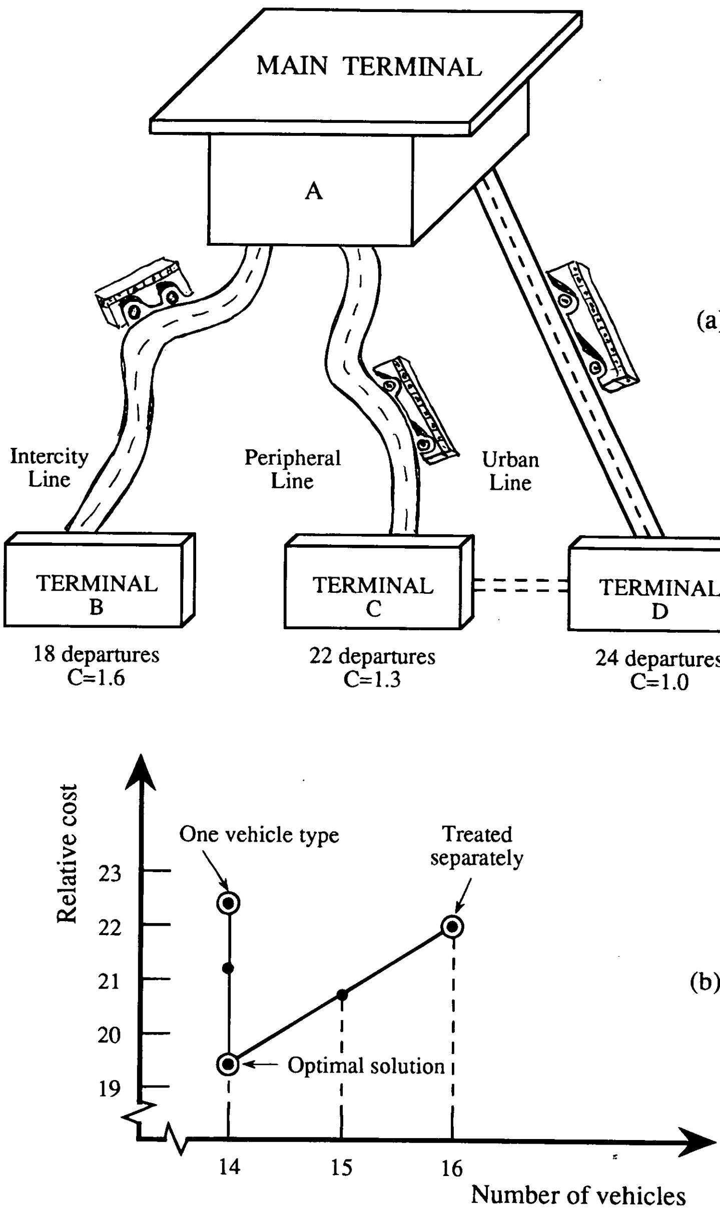

FIGURE 2 (*a*) **Schematic description of real-life scheduling problem with three types of vehicles and relative costs; (*b*) Trade-off situation between total number of vehicles and cost associated with five disparate solutions.**

Among the eight steps of the VTSP algorithm, Step 3 and particularly Step 6 deserve further attention concerning the conditions specified in these steps. The following four propositions clarify and interpret these conditions.

Proposition 1 (for Step 3) If $N_1 = N_2$, then $C_2 < C_1$.

Proof: Given $M > 2$ and $c_1 > c_2 \ldots > c_m$, the proof is straightforward because $C_1 = N_1 c_1$. $C_2 = \sum_{u=1} N_{2u} c_u$, $N_2 = \sum_{u=1} N_{2u}$, and $N_1 = N_2$.

Proposition 2 [for Step 6(*a*)] Any DH trip connection between an arrival of a trip of type u with a departure of a trip of type v such that $u < v$ within any URDHC does not increase C.

Proof: Because $c_u > c_v$, this DH trip connection cannot lead to an upgrade of the vehicle type, thus cannot increase the objection function C.

Proposition 3 [for Step 6(*b*)] Any DH trip connection between an arrival of a trip of type u with a departure of a trip of type v, such that $u > v$ within a URDHC aims at saving a vehicle of type w, such that $w < v$ does not increase C.

Proof: This DH trip connection may upgrade the vehicle type of a trip of type u (from u to v). That is, the result may be a saving of a vehicle of type w along with an upgrade of one vehicle from type u to v. As $c_w > c_v$ and $c_v > c_u$, then the net saving is always negative: $-c_w + (c_v - c_u) < 0$; thus, in any of these instances, C can only decrease.

Proposition 4 (for Step 6(*c*)) Any DH trip connection between an arrival of a trip of type u and a departure of a trip of type v, such that $u > v$ within a URDHC aims at saving a vehicle of type w, such that $w > v$ does not increase C if $c_v - (c_w + c_u) < 0$.

Proof: In this case $c_v > c_w$; hence Proposition 3 cannot be applied here. Therefore, the condition for a negative net saving is set to $-c_w + (c_v - c_u) = c_v - (c_w + c_u) > 0, w, u, v, \epsilon M$.

A REAL-LIFE EXAMPLE

The VTSP algorithm was used to examine a real-life scheduling problem. The EGGED bus company in Israel was selected, which has three different bus lines departing from a main terminal in Haifa. In Figure 2*a*, the three lines are shown schematically: intercity, peripheral, and urban. The intercity line is characterized by 18 departures in its daily timetable, with 120 min average travel time and 105 min average DH time between *A* and *B*. The peripheral line has 22 daily departures, with 45 min average travel time between *A* and *C*, average DH time of 24 min between *A* and *C*, and 36 min between *C* and *D*. The urban line has 24 daily departures, with 30 min average travel time and 15 min average DH time between *A* and *D*. The relative costs of the intercity, peripheral, and urban vehicles are 1.6, 1.3, and 1.0, respectively. The allowed shiftings $\Delta^i du = \Delta^i au = 3$ min for all trips i and vehicle type u.

The VTSP algorithm results in the optimal solution shown in Figure 2*b* with $C = 19.4$, and 14 vehicles are required: 7, 4, and 3, intercity, peripheral, and urban vehicles, respectively. Steps 1 and 2 of the algorithm result in $C = 22.4$ (14 intercity vehicles) and $C = 22$ (7 intercity, 6 peripheral, and 3 urban vehicles), respectively. This outcome of the algorithm is circled in Figure 2*b*. In addition, this figure contains two more solutions, with $C = 21.2$ (11 intercity, 2 peripheral, and 1 urban vehicles) and $C = 20.7$ (7 intercity, 5 peripheral, and 3 urban vehicles). These solutions are based on the deficit function's shifting and URDHC procedures, excluding the three conditions of Step 6 of the VTSP algorithm.

CONCLUDING REMARKS

The results of the heuristic method suggest that the VTSP algorithm also can be used for large transit agencies, ensuring efficient allocation of different vehicles to trips while reducing costs involved to a minimum level. It is worth mentioning that for further understanding of the algorithm presented, a detailed example is presented by Ceder (*7*).

Because the algorithm is based on the deficit function theory, it is recommended that the various rules contained in this theory be applied. That is, the algorithm may commence searching for the optimal solution based on different criteria: (a) shifting (departure times) first DH (trip insertion) after; (b) only DH insertions without shifting, and (c) DH with shifting simultaneously. It is worth mentioning that one of the main advantages of the deficit function is its visual nature. Consequently, one can observe, even in an automatic mode, intermediate results and evaluate them while the algorithm executes further procedures. The inevitable interaction between the setting timetable, vehicle scheduling, and crew assignment components emphasizes the importance of allowing the scheduler to understand the solution process and be able to interfere whenever he thinks it is justifiable.

REFERENCES

1. Ceder, A., and H. I. Stern. Deficit Function Bus Scheduling with Deadheading Trip Insertions for Fleet Size Reduction. *Transportation Science*, Vol. 15, 1981, pp. 338–363.
2. Stern, H. I., and A. Ceder. An Improved Lower Bound to the Minimum Fleet Size Problem. *Transportation Science*, Vol. 17, 1983.
3. Ceder, A., and H. I. Stern. Graphical Person-Machine Interactive Approach for Bus Scheduling. In *Transportation Research Record 857*, TRB, National Research Council, Washington, D.C., 1982, pp. 69–72.
4. Gertsbach, I., and Y. Gurevich. Constructing an Optimal Fleet for a Transportation Schedule. *Transportation Science*, Vol. 11, 1977, pp. 20–36.
5. Costa, A., I. Branco, and J. Paixao. Vehicle Scheduling Problem with Multiple Types of Vehicles. In *International Workshop on Computer-Aided Scheduling of Public Transport*, Springer-Verlag, Lisbon, July 1993.
6. Bertossi, A., P. Carraresi, and G. Gallo. On Some Matching Problems Arising in Vehicle Scheduling. *Networks*, Vol. 17, 1987, pp. 271–281.
7. Ceder, A. *Minimum Cost Vehicle Scheduling with Different Types of Transit Vehicles.* In *International Workshop on Computer-Aided Scheduling of Public Transport*, Springer-Verlag, Lisbon, July 1993.

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Optimal Mixed Bus Fleet for Urban Operations

KURT KER-TSHUNG LEE, SHARON H. F. KUO, AND PAUL M. SCHONFELD

A model is developed for optimizing vehicle sizes on multiple route operations in bus service. The demand characteristics are specified with regular discrete distributions that can realistically represent the variations over time. The total operator and user cost, which does not include the capital cost of vehicles in one-size operations on one route or multiple routes, is minimized by using a classical analytic optimization. Total system cost, which includes the capital cost of buying vehicles in mixed-fleet operation on one route or multiple routes, is minimized by using the numerical method in which the multidimensional optimization algorithm is applied. The optimized variables, which could be decided sequentially, are vehicle sizes, optimal headways, and operating fleet size. Computer programs are designed for optimization and sensitivity analysis. Numerical examples are presented for one-size and mixed-fleet operation on one route and multiple routes with discrete demand periods.

Optimal vehicle size is a very important issue in bus operations. Often, only one vehicle size is selected based on the peak-hour demand. The same vehicle size is then used on each route and in each time period. This is not necessarily economical, because if large vehicles are always used, user costs are high in off-peak periods, and if small vehicles are used, operator costs are high in peak periods. Mixed-fleet operation might be preferable to conventional one-size operation when the passenger demands differ widely between different time periods or among different routes. There will be a threshold in the passenger volume indicating whether to use one or two vehicle sizes. If analysis shows that mixed-fleet operation is already better than one-size operation on a single route with multiple demand periods, then mixed-fleet operation should be even more advantageous on multiple route systems, because the demand level will likely be significantly different on different routes and in different time periods.

A number of attempts have been made to optimize one vehicle size in bus operation. Most approaches have studied certain idealized problems by analytic methods. They have considered the optimal vehicle size generally with only one size and one demand period. They sought to determine the optimal vehicle size, service frequencies, and fleet size that should be used to carry passengers from distributed origins to a single destination, satisfying certain requirements. In this section the literature in the area of bus operation is reviewed. The focus is on the design or operation of a bus service in which users are served by one route or multiple routes.

Navin (*1*) developed a simple mathematical model to optimize bus size and vehicle productivity. Since London's city transit has been shown to be operating at almost optimal occupancies of 38 and 18 passengers during peak and off-peak periods, respectively, Navin's model tried to duplicate these results as well as observations of conventional commuter routes. The equations in Navin's study may be manipulated to give the "mathematically optimal" passenger productivities, vehicle occupancy and fleet size.

White and Turner (*2*) summarized recent developments in intensive minibus service in Britain. They developed a cost comparison of minibus versus conventional bus service with one-size operation on one route, and calculated the levels of demand and population density necessary to support minibus service. The total cost excluded user cost, and included capital cost, fuel consumption, maintenance cost, and labor cost. The researchers identified the needs for minibus operation throughout the day, but without vehicle size optimization.

An analytic model including vehicles size as a decision variable was developed by Oldfield and Bly (*3*). The objective in their simple bus line model was to maximize the total social benefit on one route. The passenger demand varied with the generalized cost of travel according to a constant elasticity. The concluded that operating cost increased linearly with bus size, and that the optimal size varied with the square root of demand. The analytic results indicated that the optimal bus size is smaller than the current British practice. Their study suggested an optimal capacity of about 60 seats, assuming that cost varied with size according to the average costs of current British bus operations.

Jansson (*4*) also developed an analytic model for vehicle size. His objective function value was to minimize total social costs, including the cost of passenger waiting time and ride time and the operating costs. He obtained the optimal frequency with the "square root formula" (which states that the frequency of service should be approximately proportional to the square root of the number of passengers carried on a bus line) and determined the optimal bus size by the peak demand and optimal frequency. Jansson accounted for different service frequencies in the peak and off-peak periods for the same vehicle size, and compared costs for peak and off-peak periods in numerical examples. A linear function for bus operating cost, $B = a + bS$, was used. This linear function will also be used in the present study.

Chang and Schonfeld (*5*) investigated the temporally integrated bus systems with analytic models in which fixed-route services are provided during higher-demand periods while flexible-route services are provided during lower-demand periods. They assumed demands to be fixed and uniformly distributed over time within each specified period. The researchers obtained optimized vehicle sizes by minimizing average cost per trip and compared them for fixed route, flexible route, and integrated systems. Their numerical results indicated that the optimal vehicle sizes (37 seats per vehicle) in an integrated system were a compromise between the optimal

K. K.-T. Lee, Department of Traffic Engineering and Transportation Management, Feng Chia University, Taichung, Taiwan, Republic of China. S. H. F. Kuo, Ministry of Transportation and Communications, Taiwan Area National Expressway Engineering Bureau, Taipei, Taiwan, Republic of China. P. M. Schonfeld, Department of Civil Engineering, University of Maryland, College Park, Md. 20742.

vehicle sizes for pure fixed-route (48 seats per vehicle) and pure flexible-route (17 seats per vehicle) services.

Bly and Oldfield (*6*) considered competition between minibus service and regular bus service. Their study discussed two cases: minibus operation on routes physically separated from existing large-bus services, and minibus services sharing routes with existing large-bus services. By assuming the minibus flow as a proportion of total peak bus flow, they determined the net benefit value using some specified minibus sizes on the London Transport routes. They suggested that minibuses would do well without necessarily attempting to segment the market, because most passengers were likely to accept the first bus to arrive even if it charged a little more. This shows the advantage of minibus service.

Nairn (*7*) used simulation techniques to develop and estimate the level of service, cost, and revenue for dial-a-ride services, fixed route services and mixed fleet services in a city with a population under 100,000. One conclusion was that the alternate dial-a-ride and fixed route services (mixed-fleet operation), comprising a mixed bus fleet of 45-seat vehicles for the peak period and 12-seat vehicles for the off-peak period, had lower net costs than either dial-a-ride or fixed-route services alone. They mentioned that a mixture of large and small vehicles had the potential to provide a high level of service at relatively low cost.

In summary, no previous study was found that optimized mixed bus fleet operations on multiple routes or in multiple periods. Therefore, this study focuses on the optimal mixed bus fleet for urban operation.

SYSTEM DEFINITION

The system analyzed in this study is shown in Figure 1. This study develops an optimization model for one-size operation and mixed-fleet operation in a bus system the demands of which vary over time according to discrete distributions. A fixed-route bus service network is considered in numerical examples. Each route's length, speed, and demand during each time period is different, The discrete demand on each route is shown in Figure 2. All variables and the typical values used in their numerical analysis are defined in Table 1.

The optimal vehicle sizes for mixed-fleet operation on multiple routes are the main focus of sensitivity analyses, which identify the relations between the decision variables (vehicle sizes) and various parameters.

Four main questions are addressed in this study. First, what is the threshold demand level between one-size and mixed-fleet operation

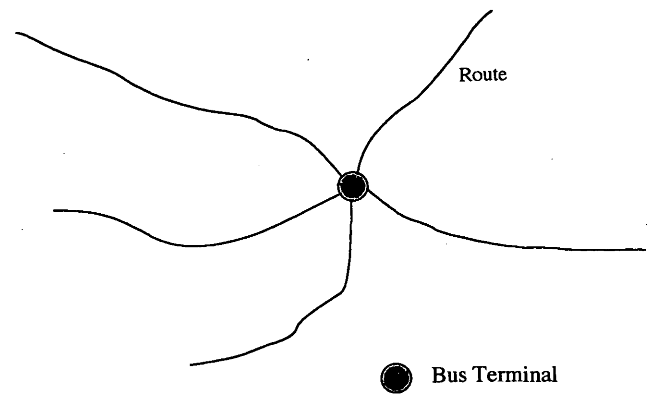

FIGURE 1 Analyzed system.

(i.e., when is the mixed-fleet operation preferable)? Second, what vehicle sizes are optimal in one-size and mixed-fleet operations? Third, what is the optimal headway on each route in each time period? Fourth, what should be the size and composition of the total bus fleet?

In describing the analytic models for the various operations, the following assumptions are made:

1. Conventional fixed-route and fixed-schedule services are provided on all routes.
2. The time required for boarding and exiting buses is included in the average speed.
3. Demands (passenger volumes) are specified with regular discrete distributions along the time periods and are invariant with price or service quality.
4. The cost of transferring vehicles among routes is negligible.

TOTAL COST FUNCTION

The objective function of these models is to minimize the sum of user and supplier cost over a full day. (A week or year may also be represented.) Both of these cost components have a major influence on the quality of bus service. Users desire frequent service on bus routes to reduce the waiting cost at bus terminals. A supplier is interested in providing the service while minimizing his cost.

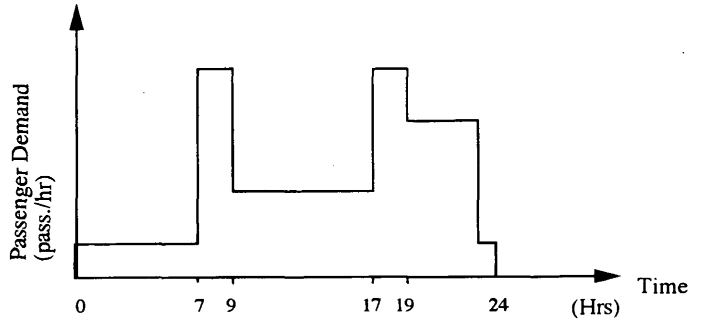

FIGURE 2 Typical passenger demand on one route in one day.

TABLE 1 Variable Definitions

Symbol	Definition	Baseline Value
a	fixed cost coefficient in vehicle operating cost ($/veh.hr.)	25.0
B	bus hourly operating cost ($/veh.hr.)	-
b	variable cost coefficient in vehicle operating cost ($/veh.seat hr.)	0.25
C	total cost ($/hr.)	-
C_o	operating cost ($/hr.)	-
C_p	the daily capital cost ($/day)	-
C_{rt}	total cost of route r in time period t ($/hr.)	-
C_{rts}	total cost of route r in period t with vehicle size s ($/hr.)	-
C_{s1}	total cost with vehicle size s1 ($/hr.)	-
C_{s2}	total cost with vehicle size s2 ($/hr.)	-
C_T	total system cost ($/day)	-
C_t	total cost in period t ($/hr.)	-
C_u	user cost ($/hr.)	-
C_v	user in vehicle cost ($/hr.)	-
C_w	user waiting cost ($/hr.)	-
c	fixed cost coefficient in vehicle capital cost ($/veh.)	16,000
D	route length (miles)	-
D_r	the length of route r (miles)	-
d	the average travel distance of boarding passengers (miles)	-
d_r	average travel distance of boarding passengers of route r (miles)	-
e	variable cost coefficient in vehicle capital cost ($/veh.seat)	2,400
G	vehicle capital cost ($/veh.)	-
H	vehicle headway (hrs.veh.)	-
H_{rt}	vehicle headway of route r in period t (hrs/veh.)	-
H_{rts}	vehicle headway of route r in period t with size s (hrs/veh.)	-
H_t	vehicle headway in period t (hrs/veh.)	-
i	interest rate	-
K	capital recovery factor with interest rate i and period N	0.1359
k	number of vehicle sizes	2
m	number of time periods	18
N	the operating fleet size (vehicles)	-
N_{rts}	the fleet size of route r in period t with size s (vehicles)	-
N_{ts}	the fleet size in period t with size s (vehicles)	-
N_s	the fleet size with size s (vehicles)	-
n	number of routes	4
Q	the passenger demand (pass.hr.)	-
Q_{rt}	the demand of route r in period t (pass.hr.)	-
Q_t	the demand in period t (pass.hr.)	-
q	the peak point demand along a route (pass.hr.)	-
q_{rt}	the peak point demand of route r in period t (pass.hr.)	-
q_t	the peak point demand in time period t (pass.hr.)	-
S	vehicle size (seats/veh.)	-
S_S	size for type s vehicles (seats/veh.)	-
T	the average economical life for buses (years)	-
V	average speed (mph)	-
V_t	average speed in time period t (mph)	-
V_{rt}	average speed of route r in time period t (mph)	-
υ_υ	time value of passenger in-vehicle time ($/pass.hr.)	6
υ_w	time value of passenger waiting time ($/pass.hr.)	10
*	superscript indicating optimal value	-

Reducing user cost increases supplier cost and vice versa. The choice of optimal vehicle sizes greatly affects the user and supplier costs. With large size(s), the supplier is favored since the corresponding headways are larger and fewer vehicles are operated. Conversely, the small vehicles will favor the user since the corresponding headways and wait times will be smaller. When the passenger demand varies over time periods, the optimal vehicle size should also vary over time. The purpose of this study is to identify the optimal vehicle size(s) which minimize the total cost of users and suppliers over a set of periods, such as one daily cycle.

The variables used in this model formulation are defined in Table 1. The two main cost components are the operator costs (C_o) and user costs (C_u). The operator cost is the product of the required fleet size, N, and hourly operating bus cost, B.

$$C_{mo} = NB = 2DB/VH \quad (1)$$

The user costs, C_u, consist of waiting cost and in vehicle cost:

$$C_u = C_{uw} + C_{uv} = (2v_w QH/2) + (2v_v Qd/V) \quad (2)$$

The total cost, C, is the sum of operator cost and user cost:

$$C = C_o + C_U = 2DB/VH + v_w QH + 2v_v Qd/V \quad (3)$$

A linear bus hourly operating cost function of the type used by Jansson (1980) is also used here:

$$B = a + bS \quad (4)$$

The above equation will be used to optimize the vehicle size S.

With the capacity constraint, $H \le S/q$, the total cost function becomes:

$$C = [2Dq(a + bS)/VS] + v_w SQ/q + 2v_v Qd/V \quad (5)$$

The vehicle size (S) that minimizes the total cost (C) can be found by setting the derivative of C with respect to S equal to zero and solving.

$$\delta C/\delta S = (-2aDq/VS^2) + v_w Q/q = 0 \quad (6)$$

The second-order derivative of C is as follows.

$$\delta^2 C/\delta S^2 = 4aDq/VS^3 \quad (7)$$

Because all variables in Equation 7 are positive, the second-order derivative of C with respect to S is positive. Therefore, Equation 6 will yield the S value for a minimum rather than maximum total cost. The optimal vehicle size (S^*) is as follows.

$$S^* = (2aDq^2/v_w VQ)^{0.5} \quad (8)$$

S^* = the optimal vehicle size (seats per vehicle) for one route where total cost is minimized.

Therefore, the corresponding optimal headway that satisfies demand is as follows.

$$H^* = S^*/q = (2aD/v_w VQ)^{0.5} \quad (9)$$

The fleet size of each route is as follows.

$$N = 2D/VH^* \quad (10)$$

As determined above, the optimal vehicle size (S^*), the practical optimal headway (H), and fleet size (N) are only suitable for one specified time period on each route.

Actually, there are different passenger volumes in different periods. Often, a bus company will use the peak period volume to determine the vehicle size (S) and the fleet size (N). If only one vehicle size (large) is used, based on the peak period passenger volume, the user cost will be higher in off-peak periods because the headway with the large vehicle will be too large. Conversely, there will be higher operating costs in peak periods if the small vehicle size is used, based on the off-peak volume.

One Size–Multiple Routes–Multiple Periods

If one-size operation is used on multiple routes in multiple periods, the procedures for determining the optimal vehicle size should be modified as follows.

For the capacity requirement ($H_{rt} \le S/q_{rt}$) the total cost function becomes the following.

$$C_T = \sum_{r=1}^{n} \sum_{t=1}^{m} \{[2D_r q_{rt}(a + bS)/V_{rt}S] + (v_w SQ_{rt}/q_{rt}) + (2v_v Q_{rt} d_r/V_{rt})\} \quad (11)$$

where C_T = the total cost for all routes and all times periods (dollars per day).

The vehicle size (S) that minimizes the total cost (TC) can be found by setting the derivative of TC with respect to S equal to zero and solving.

$$\delta C_T/\delta S = \left(\sum_{r=1}^{n} \sum_{t=1}^{m} - 2aD_r q_{rt}/V_{rt}S^2\right) + \left(\sum_{r=1}^{n} \sum_{t=1}^{m} v_w Q_{rt}/q_{rt}\right) = 0 \quad (12)$$

The second derivative of C_T is as follows.

$$\delta C_T/\delta S^2 = \sum_{r=1}^{n} \sum_{t=1}^{m} 4aD_r q_{rt}/V_{rt}S^3 \quad (13)$$

Because all variables in Equation 13 are positive, the second derivative of TC with respect to S is positive. Therefore, Equation 13 will yield the S value for a minimum rather than maximum total cost. The optimal vehicle size (S^*) is as follows.

$$S^* = \left[\sum_{r=1}^{n} \sum_{t=1}^{m} (2aD_r q_{rt}/V_{rt}) \,/\, (\sum_{r=1}^{n} \sum_{t=1}^{m} v_w Q_{rt}/q_{rt}\right]^{0.5} \quad (14)$$

where S^* = the optimal vehicle size for one route (seats per vehicle) where total cost is minimized.

Therefore, the corresponding optimal headway of route r in time period t that satisfies the demand is as follows.

$$h_{rt} = S/q_{rt} \quad (15)$$

$$h_{rt} = \left[\sum_{r=1}^{n} \sum_{t=1}^{m} (2aD_r q_{rt}/V_{rt})/(\sum_{r=1}^{n} \sum_{t=1}^{m} v_w Q_{rt}/q_{rt}\right]^{0.5} / q_{rt} \quad (15a)$$

where h_{rt} = the corresponding headway of route r in time period t (hrs/vehicle).

The optimal headway for each route in each demand period which minimizes the total cost can be found by setting equal to zero the derivative with respect to headway (H_{rt}) of the total cost of route r at time period t (C_{rt}).

$$C_{rt} = 2D_r(a + bS)/V_{rt}H_{rt} + v_w Q_{rt}H_{rt} + 2v_w Q_{rt} d/V_{rt}) \quad (16)$$

$$\delta C_{rt}/\delta H_{rt} = [-2D_r(a + bS^*)/V_{rt}H_{rt}^2] + v_w Q_{rt} = 0 \quad (17)$$

The second-order derivative of C_{rt} is as follows.

$$\delta^2 C_{rt}/\delta H_{rt}^2 = 4D_r(a + bS^*)/V_{rt}H_{rt}^3 \quad (18)$$

Because all variables in Equation 18 are positive, the second-order derivative of C_{rt} with respect to H_{rt} is positive. Therefore,

Equation 18 will yield the H_{rt} value for a minimum rather than maximum total cost. The optimal value of H_{rt} is as follows.

$$H^*_{rt} = [2D_r(a + bS^*)/Q_{rt}v_w V_{rt}]^{0.5} \tag{19}$$

The practical optimal headway H_{rt} is either the optimal headway H_{rt}* from Equation 19, which minimizes costs, or the maximum headway h_{rt} from Equation 15a, which satisfies demand, whichever is smaller.

$$H_{rt} = \text{Min}\ \{[2D_r(a + bS^*)/Q_{rt}v_w V_{rt}]^{0.5}, \left[\sum_{r=1}^{n}\sum_{t=1}^{m}(2aD_r q_{rt}/V_{rt})/\left(\sum_{r=1}^{n}\sum_{t=1}^{m}v_w Q_{rt}/q_{rt}\right)\right]^{0.5}/q_{rt}\} \tag{20}$$

The fleet size of route r in time period t is as follows.

$$N_{rt} = 2D_r/V_{rt}H^*_{rt} \tag{21}$$

These equations are used to obtain the optimal vehicle size by minimizing the sum of operating cost and user cost, but do not include the capital cost of the vehicles. Therefore the optimal vehicle sizes, which can be obtained by the analytic solutions of Equations 8 and 14, are only the approximate solutions, the objective function of which does not include the capital cost. The reason the analytic solutions cannot be obtained if the capital cost is included in the objective function is as follows: the capital cost is a function of the fleet size required and the vehicle size, while the fleet size is also a function of vehicle size. The fleet size that has to be available for any vehicle size is the maximum fleet required for that size through all the periods. This maximum function cannot be differentiable.

Capital Cost

In mixed-fleet operation, if two vehicle sizes are used on one route, the capital cost will be higher because the operator must buy two kinds of vehicles. However, if two sizes are used on multiple routes, the capital cost may be lower because the operator can share the vehicles on different routes in different time periods.

In general, the operating fleet size on each route in each period with the specified vehicle size can be formulated as follows.

$$N_{rts} = 2D_r/V_{rt}H_{rts} \tag{22}$$

The total operating fleet size for all routes in each time period with the specified vehicle sizes can be expressed as follows.

$$N_{ts} = \sum_{r=1}^{n} 2D_r/V_{rt}H_{rts} \tag{23}$$

The minimum fleet size required with the specified vehicle size is as follows.

$$N_s = \underset{t=1}{\overset{m}{\text{Max}}}\ (N_{ts}) \tag{24}$$

The capital cost function for vehicles can be formulated as follows.

$$G = c + eS_s \tag{25}$$

The capital cost per day can be formulated as follows.

$$C_p = \sum_{s=1}^{k} \{[(c + eS_s)(A/P,i,T)/365]^*N_s\} \tag{26}$$

where $(A/P, i, T) = k =$ the capital recovery factor with interest rate i and time period T.

Two Sizes–Multiple Routes–Multiple Periods

Because there are advantages in using two different sizes of vehicle to operate only one route when the demand level is extremely different in different time periods, it is worth attempting two-vehicle-size operation on multiple routes (large vehicles for high-demand periods and small vehicles for low-demand periods). The total cost of mixed-fleet operation on multiple routes with the route r, time period t, and vehicle size s_s can be obtained from the following equation.

$$C_{rts} = [2D_r q_{rt}(a + bS_s)/V_{rt}S_s] + v_w S_s Q_{rt}/q_{rt} + 2v_v Q_{rt}d_r/V_{rt} \tag{27}$$

The total cost of a bus system with multiple routes and multiple demand periods can be formulated as follows.

$$C_t = C_p + \sum_{\text{all } r}\sum_{\text{all } t}\sum_{\text{all } s} C_{rts} = C_p + \sum_{r=1}^{n}\sum_{t=1}^{m}\sum_{s=1}^{k}[2D_r q_{rt}(a + bS_s)/V_{rt}S_s] + v_w S_s Q_{rt}/q_{rt} + 2v_v Q_{rt}d_r/V_{rt} \tag{28}$$

The capital cost (C_p) can be obtained from Equations 22–26. The optimal vehicle size (S*) should be the size with the minimum total cost of all time periods (C_t). The corresponding optimal headway and operating fleet size may be found with Equations 20 and 21.

Demand Boundary Among Different Vehicle Sizes

Conceptually, large vehicles should be used in high-demand periods and small vehicles should be used in the low-demand periods. If two prespecified vehicle sizes are used on a single route or on multiple routes, conceptually, a boundary expressed in terms of demand might indicate when the larger size should be used instead of the smaller size. According to Equation 8, q^2D/QV should serve as a very good combined factor for the boundary between using large or small vehicles.

If two prespecified vehicle sizes operate on one route in one specified time period, the total cost with respect to the two different vehicle sizes can be formulated as follows.

$$C_{s1} = [2Dq(a + bS_1)/VS_1] + v_w S_1 Q/q + 2v_v Qd/V \tag{29}$$

$$C_{s2} = [2Dq(a + bS_2)/VS_2] + v_w S_2 Q/q + 2v_v Qd/V \tag{30}$$

When Equations 29 and 30 are set to be equal, the following equation can be obtained.

$$q^2D/QV = v_w S_1 S_2/2a \quad (31)$$

Therefore, the boundary variable q^2D/QV can be obtained by Equation 31. By comparing the q^2D/QV of each route in each time period with the boundary $v_w\ S_1S_2/2a$, the choice of a large or small vehicle can be made for each route and in each time period. It is very important to note that the boundary q^2D/QV is only a function of the time value of passengers, vehicle sizes, and the fixed cost coefficient in vehicle operating cost function (Equation 8 shows the same relations). Clearly, when vehicle sizes are larger, the boundary should be higher. When the time value of passengers is higher, the boundary will also be higher, because it will favor the small vehicles. It is also interesting to note that if the fixed cost coefficient in the vehicle operating cost function increases, it favors the vehicles and the boundary decreases.

In numerical examples in this study, the maximum load on the route (q) is set to be equal to the total passengers boarding on that route, Q. (That would happen, for instance if all passengers go to the central business district in the morning and return in the evening.) Therefore Equation 31 can be simplified as follows.

$$QD/V = v_w S_1 S_2/2a \quad (31a)$$

OPTIMIZATION FOR MIXED FLEET

When two vehicle sizes are operated, a multidimensional optimization method is needed to optimize vehicle sizes. The objective function includes a maximum choice function. This cannot be solved analytically, because it cannot be differentiated with respect to the decision variables (vehicle sizes). A quasi-Newton method with finite-difference gradient has been used in this study to find an approximate initial solution for the optima.

IMSL routine UMINF was chosen for the multidimensional optimization in this study. This routine used a quasi-Newton method with finite-difference gradient to find the minimum of a function $[f(x)]$ of n variables, and is documented in the user's manual of *Fortran Subroutines for Mathematical Applications* (*8*). To determine the best vehicle size combination (S_1^*, S_2^*), corresponding headways, and fleet sizes on multiple routes, the procedures are as follows.

1. Choose the highest passenger volume and the lowest passenger volume from the periods in one day for all routes.
2. Initialize two vehicle sizes, using the highest and lowest passenger volumes by Equation 8 to be the upper and lower bounds of the possible vehicle sizes.
3. Determine the passenger-demand boundary between the large and small vehicle sizes with Equation 31.
4. Find the corresponding headway on each route in each period with Equation 20.
5. Determine the total fleet size for multiple routes with the combination of different vehicle sizes using Equations 22–26.
6. Calculate the total cost for multiple routes for all periods with Equation 28.
7. Use the UMINF quasi-Newton program to search for a two-vehicle-size combination with a smaller total cost (repeat Procedures 3–7) until the best combination with the minimum total system cost is found.
8. Use the optimal two-vehicle-size combination to obtain the corresponding optimal headway (H_{rt}^*) with Equation 20 and the operating fleet size (N_{rt}) with Equation 21.

In mixed-fleet operation, the fleet size for each vehicle size can be adjusted by violating the boundary (and using the "wrong" size across the boundary); doing so may reduce the total cost by reducing total fleet size and capital cost. The adjustment procedures are as follows:

1. Rank periods in order of decreasing demand as shown in Figure 3.
2. Referring to Figure 3, identify the boundary route (z_t) with the demand closest to the boundary in period t.
3. Substitute small or large vehicles on route z_t in period t.
4. Recompute the total fleet size (N_{ts}) in period t according to Equations 22–26.
5. Check whether the size substitution is necessary (N_{ts} must be greater than the fleet size in other periods).
6. If the size substitution is necessary, compute the total cost with the new total fleet size.
7. If the new cost is less that the old total cost, accept the substitution for new fleet size.
8. Repeat Procedures 1–6 for next boundary route in the next period.

The concept for assigning vehicles to each route in each period is shown in Figure 3. Only one boundary is shown since only two vehicle sizes are considered for the mixed-fleet operation in this study. If n sizes are used there will be $(n - 1)$ boundaries.

NUMERICAL EXAMPLE

The numerical examples for the various operations shown below are simplified as follows:

1. There are only two different passenger-demand periods in one day (peak demand for 4 hours and off-peak demand for 14 hours);
2. There are only two kinds of speed in 1 day (peak and off-peak); and
3. Only one or two vehicle sizes are operated.

In peak periods, the speed is lower, and the demand is higher than in off-peak periods. By using the demand, speed, and distance information from Table 2 the numerical results shown in Table 3 are obtained for four cases of bus operation.

The optimal two-vehicle-size combination is (33, 20) seats per vehicle, and the total fleet consists of 15 large vehicles and 29 small vehicles. The total fleet size (44 vehicles) is lower than the total fleet size for one-size (48 vehicles).

In these multiple-route examples, two-size operation will reduce total system cost by $753 per day, compared to one-size operation. Not only is the operation and user cost lower (the difference is $746 per day) but the capital cost is lower as well (the difference is $7 per day), because the fleet size is reduced. The reason is that multiple routes can share the large or small vehicles in different periods.

If sizes are independently optimized for each route, mixed-fleet operation will reduce total system cost by $65 per day. Compared

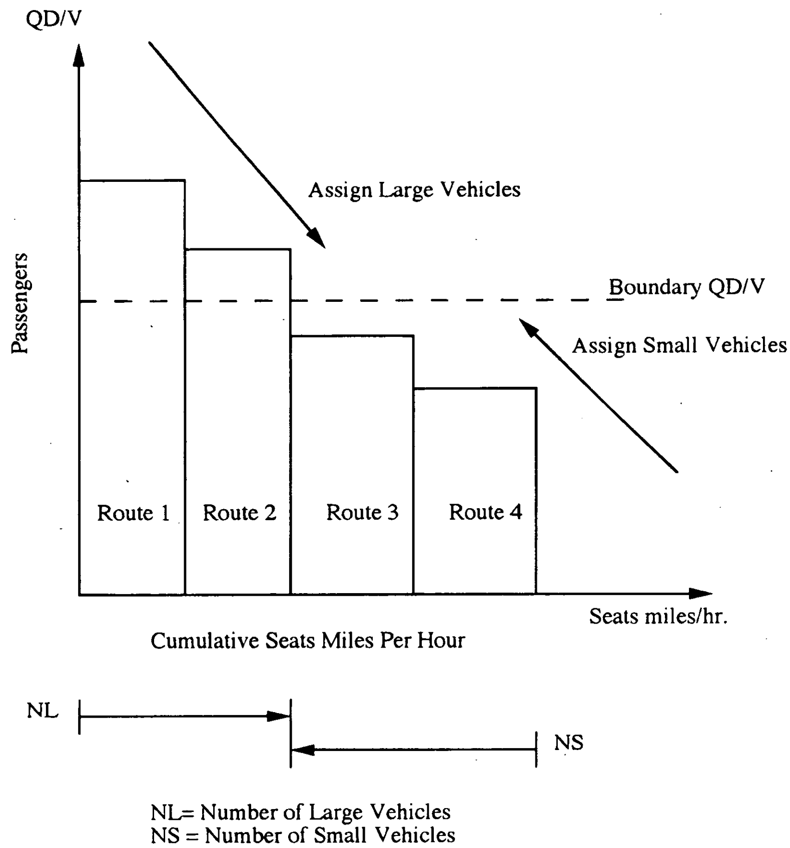

FIGURE 3 Procedures in assigning vehicles to each route in each period.

to one-size operation, the operation and user cost is significantly reduced by $609 per day; however, the capital cost increases by $544 per day in two-size operation because more, and different, vehicles are needed.

It is interesting to note that the total cost of one (different) independently optimized size on each route is less than the total cost of a systemwide size because no compromise among routes is necessary. For each route the vehicle size can be adjusted to demand. Similarly for mixed-fleet operation, the independent operation on each route is slightly better than the same systemwide two-size combination operation on all multiple routes.

TABLE 2 Demand, Speed, and Distance Information for Multiple Route System

Route	Distance (Kms)	Speed (kph)		Demand (pass./hr.)	
		Peak	Off-peak	Peak	Off-peak
1	16	40	48	200	100
2	20	40	48	300	150
3	16	40	48	150	60
4	24	40	48	400	200

The UMINF quasi-Newton program is designed to optimize continuous functions and its solutions are real numbers. Actually, possible vehicle sizes should be integer number of seats. Thus, the nearby integer solutions should be checked to obtain the optimal sizes. In the numerical example, the optimal vehicle sizes on multiple routes were (32.876, 20.221), from which (33, 20) was found to be the optimal integer solution.

These numerical results show that the mixed-fleet operation is preferable when the peak period demand is significantly different from the off-peak demand. To identify the threshold demand in choosing between one-size or mixed-fleet operation, the off-peak demands were fixed for all routes, and the peak demands were increased by multiples of the off-peak demand. The mixed-fleet operation is preferable for the data in Table 2. To determine the effects of passenger demand on the choice between one-size or mixed fleet operation, a very low off-peak demand (40 passengers per hour) was assumed on each route for both one-route and multiple route operation. The threshold ratio of peak demand to off-peak demand for multiple route operation is identified in Figure 4.

Figure 4 shows that the threshold ratio of peak demand to off-peak demand for multiple-route operation is 1.92. This shows that mixed-fleet operation is preferable on multiple-route operation when the demand variation is higher.

Figure 5 shows the relation between the passenger demand boundary and the total cost for mixed-fleet operation on multiple routes. This relation is not smooth because the demands on four

TABLE 3 Comparison of One-Size and Two-Size Operation on Multiple Routes

Items	One Size Each Route	One Size Systemwide	Two Sizes Each Route	Two Sizes Systemwide
R	10-40	10-40	10-40	10-40
S^*	-	22	-	(33, 20)
$S1^*$	18	-	(21, 14)	-
$S2^*$	22	-	(24, 15)	-
$S3^*$	16	-	(20, 11)	-
$S4^*$	27	-	(36, 23)	-
$H1_p^*$	0.090	0.110	0.105	0.100
$H2_p^*$	0.073	0.073	0.080	0.067
$H3_p^*$	0.107	0.128	0.127	0.127
$H4_p^*$	0.068	0.055	0.090	0.083
$H1_f^*$	0.140	0.143	0.138	0.141
$H2_f^*$	0.116	0.116	0.107	0.115
$H3_f^*$	0.180	0.184	0.176	0.183
$H4_f^*$	0.126	0.110	0.115	0.100
N^*	-	48	-	(15, 29)
$N1^*$	9	8	(8, 5)	-
$N2^*$	11	11	(11, 7)	-
$N3^*$	8	7	(7, 4)	-
$N4^*$	18	22	(14, 9)	-
C_o	29,904	31,029	30,877	30,424
C_{uw}	25,528	24,946	23,946	24,805
C_{uv}	58,160	58,160	58,160	58,160
C_{uo}	113,592	114,135	112,983	113,389
C_p	1,185	1,230	1,729	1,223
C_t	114,777	115,365	114,712	114,612

routes and two time periods are discrete. This relation should change to an approximately continuous U-shape when the number of routes or number of time periods of each route, or both, increases significantly.

CONCLUSIONS AND RECOMMENDATIONS

The models presented herein may be used to determine the optimal vehicle sizes for mixed-fleet operation on single or multiple routes. The main advantages of these models over previous studies include the following points.

1. These models can deal with mixed-fleet operations.
2. They can deal with vehicle size, fleet combinations, and vehicle assignment by including capital, operation, and user costs in objective function.
3. They can deal with demand variation over multiple periods.
4. They can be used to assign vehicles and determine the optimal headways for operation on multiple routes, and can help optimize vehicle and fleet sizes for planning purposes.

General conclusions and specific finding are presented as follows.

1. It may be advantageous to use two vehicle sizes on a single route when the demand level is very different in different time periods.
2. It is preferable to use a mixed fleet on multiple routes when demand variation over time is significant.
3. The required fleet size for mixed-fleet operation may be lower than the fleet size for one-size operation, thereby reducing the capital cost.
4. Using the boundary demand developed in this study to choose between different size vehicles, the operator can easily assign the vehicles to each route in each time period.
5. The results of the sensitivity analyses show that the proposed optimization algorithm can provide consistent and reasonable responses to various changes.

These relations can provide the operators with good guidelines for designing or operating bus routes efficiently. The mathematical

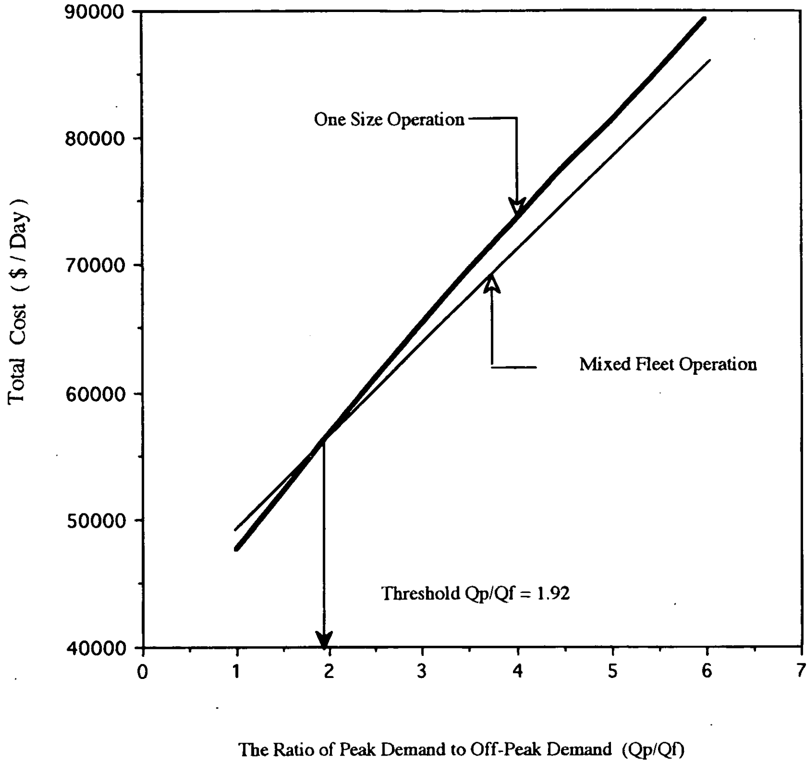

FIGURE 4 Threshold passenger-demand ratio in using one-size or mixed-fleet operation on multiple routes.

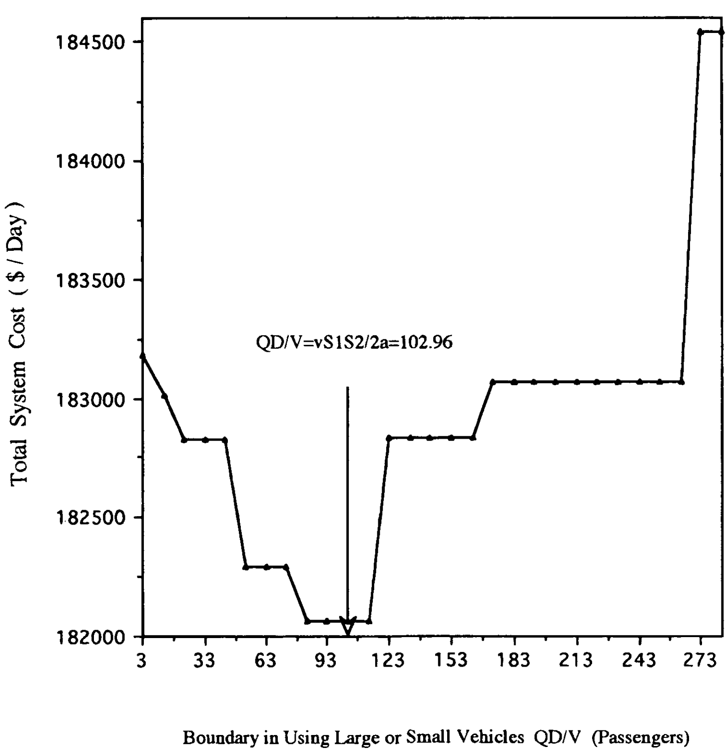

FIGURE 5 Relationship between passenger-demand boundary and total cost of mixed-fleet operation on multiple routes.

relations developed here provide useful guidelines for optimizing the vehicle sizes for one-size or mixed-fleet operations. The output from this approach can be used for planning or operating purposes. This is particularly useful to planners and operators contending with difficult factors, such as the rules for assigning vehicles on multiple routes.

Several possible extensions of the numerical analyses and analytic model developed in this research can be suggested.

The validity of some assumptions should be reexamined. Passenger demand is assumed to be inelastic in this research. A model with inelastic demand cannot properly address fare policy or optimize systems for objectives that include consumer surplus. Therefore, the passenger demand should vary with the amount of the fare and the level of service provided. The objective function should be modified to maximize profit or maximize social welfare (net social benefit).

Other assumptions can also be relaxed. For instance, the analyzed system could be used as a transfer terminal in which the transfer cost should be included in the total cost function. Another possibility is that the analyzed system could be extended to flexible route operation or integrated bus systems, in which fixed services are provided during higher demand periods while flexible-route services are provided during lower demand periods.

Only two sizes for mixed-fleet operation are considered in this study. Although more than two sizes may not be worth attempting because of the difficulties in operation and maintenance, more complex mixtures are still worth investigating.

The total fleet size formulated here is only an absolute minimum. In practice, total fleet size should include spare vehicles, which are needed for bus schedule reliability and for vehicle maintenance. The optimal number of reserve vehicles should also be considered in further studies.

REFERENCES

1. Navin, P. D. Optimal Urban Bus Size. In *Transportation Research Record 633*, TRB National Research Council, Washington, D.C., 1978, pp. 74–76.
2. White, P. R. and R. P. Turner. Development of Intensive Urban Minibus Services in Britain. *Logistics and Transportation Review*, Vol. 4, 1988, pp. 385–400.
3. Oldfield, R. H. and P. H. Bly. An Analytic Investigation of Optimal Bus Size. *Transportation Research*, Vol. 22B, No. 5, 1988, pp. 319–337.
4. Jansson, J. O. A Simple Bus Line Model for Optimization of Service Frequency and Bus Size. *Journal of Transport Economics and Policy*, Vol. 14, No. 1, 1980, pp. 53–80.
5. Chang, S. K. and P. Schonfeld. Integration of Fixed and Flexible Route Bus System. *Transportation Research Record 1308*, TRB, National Research Council, Washington, D.C., 1991, pp. 51–57.
6. Bly, P. H. and R. H. Oldfield. Competition Between Minibuses and Regular Bus Services. *Journal of Transport Economics and Policy*, Vol. 20, No. 1, 1986, pp. 47–68.
7. Nairn, R. J. Dial-a-Ride and Mixed Fleet Levels of Service, Costs and Revenues in a Small City. *Proceedings of Workshop of Paratransit: Changing Perceptions of Public Transport*, Director General of Transport, Adelaide, South Australia, 1979, pp. 209–227.
8. *Fortran Subroutines for Mathematical Applications, IMSL User's Manual.* IMSLS, Inc., Houston, Tex., 1987.

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Operational Characteristics of Paratransit in Developing Countries of Asia

TOSHIKAZU SHIMAZAKI AND MD. MUKITUR RAHMAN

In many cities of developing countries, more than half of the total public transport demand is served by paratransit. Rapid increases in urban population and per capita income, along with inadequate existing transport infrastructures, have stimulated paratransit usage as inexpensive and convenient public transport modes. A comparative study of their operational characteristics is presented in order to provide basic data for discussion of urban transport issues in developing countries. Some future directions are given to increase their efficiency and thus to improve urban mobility.

Paratransit, or an informal public transport mode, has been developed to fill the gaps left by the use of private cars, buses, and fixed track systems. The functional definition of paratransit states: "Paratransit is urban passenger transportation service usually in highway vehicles operated on public streets and highways in mixed traffic; it is provided by private or public operators and it is available to certain groups of users or to the general public, but adaptable in its routing and scheduling to individual user's desire in varying degrees" (*1*). The concept of paratransit, however, differs in developed and developing countries. In developed countries, paratransit is often used for demand-responsive systems such as shared-ride taxis and dial-a-ride. In developing countries, the lower standard of living, high population density, availability of cheap labor, and so forth have provided paratransit, bridging the gap between public bus and private automobiles.

Although various forms of paratransit modes exist in developing countries, the motorized paratransit modes are dominant. For example, 70 percent of the total public transport demand in Metro Manila (Philippines), 50 percent in Jakarta (Indonesia), 40 percent in Kuala Lumpur (Malaysia), and 21 percent in Bangkok (Thailand) are carried by motorized paratransit (*2*). They provide a flexible and frequent service to small settlements and through narrow streets, where no other services are available at a low fare. In addition, the urban paratransit sector generates large employment opportunities, as much as 10 to 20 percent of the total employment (*2*).

The operational characteristics of paratransit in developing countries are compared to provide basic data for discussion of urban transport issues in developing and developed countries.

CLASSIFICATION OF PARATRANSIT IN URBAN TRANSPORTATION SYSTEM

Although the characteristics of paratransit differ based on their function in different cities, these modes are the usual means of movement among low income people and have some common characteristics such as cheap fares, low energy requirements, higher labor intensity, and small area of coverage. Generally, paratransit can be classified into two types, nonmotorized and motorized. The nonmotorized paratransit includes animal powered and human powered. The human powered is mainly hand drawn or pedal driven. Both motorized and nonmotorized systems are again subclassified into three types; individual (seating capacity < 4), shared (5–10) and collective (>11) (Table 1). Most nonmotorized paratransits are of individual type with seating capacity of 2. On the other hand, seating capacity of motorized paratransit ranges widely from 2 to 18. Sometimes, however, passengers of 2 to 3 times of capacity ride on.

As for the functional characteristics, the "individual" type paratransits provide door to door service. For the "shared" and "collective" types, the routes are generally fixed but vehicles often deviate from the route on passenger demand. The collective type of paratransit sometimes cuts routes to pick up opposite-direction passengers.

Recently, nonmotorized paratransit has been restricted in some cities' central business districts. Although more than half of the public transport passengers in Dhaka are carried by the nonmotorized paratransit, rickshaws are banned from entering some major streets. In Jakarta, Becaks have been illegal since 1990 and have almost disappeared. They are being faded out also in other Indonesian cities. In the Philippines, its use is limited to some cities.

OPERATIONAL CHARACTERISTICS OF PARATRANSIT

Service Condition

Table 2 shows the operational/service characteristics of paratransit modes in different countries. Daily travel distance of individual type paratransit ranges from 30 km by Cycle Rickshaw to 116 km by Auto Rickshaw in India. Normally nonmotorized vehicles make shorter trips than motorized ones. As a summary, nonmotorized vehicles travel daily less than 30 km, the passenger journey length is less than 5 km, and daily passenger handling is less than 25. On the other hand, motorized vehicles travel daily more than 70 km, the passenger journey length is more than 3 km, and daily passenger handling is more than 40.

According to a survey in 1984, Metro Manila was a motorized vehicle dependent city (Table 3). Although the demand for Tricycles has been increasing rapidly with the growth of scattered residential areas, it is not large because passengers can use the well-developed Jeepney system and because Tricycle and Pedicabs are banned on major roads. Tricycle users do not belong to any particular income group, and the low income group prefers Jeepney to

T. Shimazaki, Department of Civil Engineering, College of Science and Technology, Nihon University, 1-8, Kanda Surugadai, Chiyoda-ku, Tokyo 101 Japan. Md. M. Rahman, Asian Engineering Consultant, 9th Fl. Sathorn Thani Bldg., 90 North Sathorn Rd., Bangkok 10500 Thailand.

TABLE 1 Example of Classification System of Paratransit Modes in Developing Countries

Country	Non-motorized Individual	Motorized Individual	Shared type	Collective type
Bangladesh	R(2)	Auto R(2-3) Misuk(4)	Auto Tempo(6-10)	
India	Tonga(2) CR(2) Hand R(1)	T scooter R(2) MCR(4)	Trekker(9)	Tempo(14)
Indonesia	Dokar(2) Delman(2) Becak(2)	Bajaj(2-3) Ojek(2) Helicak(2)	3 wheel Bemo(7) 4 wheel Bemo(10) Opelet(7-9)	Large Opelet(17)
Malaysia	Trishaw(2)			Bus mini(16)
Nepal	CR(2)	Meter tempo(2)	Tempo(6-7)	
Pakistan	Tonga(2-4)	MR(2)		
Philippine	Calesa(2) Pedal T(2)	T(2)		Jeepney(14-18)
Sri Lanka		Auto(2-3)		
Thailand	R(2) T(2)	Samlor(2-3) Hired MC(1)	Silor(6-8)	Pickup(14)
Vietnam	Xiclos(2)	Selam(4-5)		

NOTES: The values in the parenthesis indicate the capacity (person) of each paratransit modes
R = Rickshaw, M = Motor, T = Tricycle, C = Cycle
Source: (2)

TABLE 2 Operational Characteristics of Paratransit Modes in Different Countries

City/ Country	Modes	Daily Travel (Km/Day)	Avg. PaxKm	Pax/Day	Trips /Day	Pax /Trip	Load Factor
Bangkok	Samlor			60	23.2	2.6	
	Silor			58.3	18.1	3.2	
	Hired Motorcycle			35.5	33.8	1.1	
Bangladesh	Rickshaw		3.0-6.0	26-35	30-40		
	Auto rickshaw		8.0				
India	Auto rickshaw	116	4.2	46	26	1.8	0.7
	Cycle rickshaw	30	1.9	23	13	1.8	0.8
Indonesia	Becak	20	1.5-2.5				
	Bajaj	70	3.0-5.0				
	Bemo	70	4.5-10.0				
Philippines	Jeepney	166.3	5.8	273	14	19.5	0.6

Sources: (6), (10), (11), (13), (14)

TABLE 3 Modal Split by Income in Metro Manila

Household income (Peso/month)	No of Household(%)	Modal Split(%)(1) Jeepney	Bus	Others(2)
<500	13.4	73.3	17.1	9.6
501-1000	48.3	50.8	32.7	16.5
1001-2500	31.3	69.0	22.6	8.4
2501-4000	5.0	66.1	26.3	7.6
>4001	2.0	65.4	29.0	5.6
Total	100.0	64.9	25.6	9.5

Note (1)=Exclude Taxi,
(2)=Mostly Tricycle
Source: (14)

TABLE 4 Modal Share of Passengers with Trip Distance in Manila

Trip Distance	Jeepney		Bus		Jeepney+Bus	
(Km)	'000	%	'000	%	'000	%
0.0- 1.5	902	11	0	0	902	9
1.6- 2.5	1357	17	20	1	1377	13
2.6- 5.0	2891	37	192	8	3083	30
5.1- 7.5	1882	24	656	27	2538	25
7.6-10.0	628	8	753	31	1381	13
10.1-15.0	165	2	511	21	676	7
> 15	59	1	297	12	356	3

* Exclude taxi and tricycle
Source: (15)

TABLE 5 Frequency of Bus and Jeepney in Manila

	Route length (Km)					
Mode	<5	5-10	10-20	20-30	>30	Avg.
Jeepney	78	44	24	26	18	38
Bus	18	7	9	10	10	11

Source: (15)

Tricycle even at the same fare level (Table 3). Most trips by public transport occur within a distance of 2.5 to 7.5 km, and the Jeepney captures about 85 percent of the demand of this distance (Table 4). The majority of bus passengers travel 7.6 to 10 km compared to 2.6 to 5 km by Jeepney, indicating that average trip distance by bus is longer than Jeepney. The bus and Jeepney are directly competitive in the trip length of 5 to 7.5 km. The higher competitive power of the Jeepney in the shorter trip distances is attributed to its high frequency which is 3.5 times higher than the bus even on average (Table 5). The hourly passenger capacity carried by Jeepney and bus is almost the same for a short distance. But above this range hourly capacity of the bus is almost twice that of the Jeepney.

A survey in 1992 for Metro Manila indicates, however, that the share of nonmotorized paratransit is as high as 20% (*3*). These areas are not served by bus or Jeepney, and they use nonmotorized paratransit for short distance trips for shopping or other purposes.

In India, the average journey speed including waiting time of a Cycle Rickshaw is almost the same as the bus and minibus, although vehicle speed differs among bus, minibus, and Cycle Rickshaw (Table 6). This is due to much shorter access and waiting time for a Cycle Rickshaw than for a minibus or a bus. For shorter trip distance, the shorter access and waiting time reduce the total journey time significantly. Thus, paratransit looks convenient for short distance as compared to the bus.

Passenger-handling capacities of paratransit and buses in Bangkok and India are shown in Table 7. In India, twice as many daily passengers are carried by Auto Rickshaw than by Cycle Rickshaw due to the speed differences. Although a vast difference is observed in passenger-handling capacities, the individual output of paratransit along with their large numbers has played a significant role in urban public transport.

Finally, unlike conventional bus service, the paratransit modes have no obligation to provide a service on routes where demands are low. The operator provides service only when profitable for him. Often the shared and collective types of paratransit do not leave the terminal until the vehicles are full, and this leads to a longer waiting time.

Vehicle Ownership

Most paratransit is owned and operated by private enterprise. Some survey results indicate that drivers rent the vehicles from small-scale enterprises, and very few drivers own their vehicles (Table 8).

TABLE 6 Service Characteristics of Indian Paratransit

Modes	Avg. Waiting Time (Min)	Avg. Journey Time (Min)	Avg. Journey Speed (Km/Hr)	Avg. In-Vehicle Speed (Km/hr)
Cycle rickshaw(1)	3.7	15.8	8.9	12.6
Auto rickshaw(2)	3.0	13.1	17.4	27.0
Tonga		16.9	9.9	
Mini bus(3)	11.7	36.3	12.5	17.9
Bus	12.5	46.1	12.0	16.3

(1) = Average values of 3 cities
(2) = Average values of 2 cities
(3) = Average values of 5 cities
Source: (13)

TABLE 7 Passenger-Handling Capacity of Paratransit Modes and Buses

Country /City	Modes	Passengers /Day	Passengers Kms/Day
Bangkok	Samlor	60	
	Silor	58.3	
	Hired Motor cycle	35.5	
	Bus (Reg. +Air. con)	1300	7800
	Minibus	521	1719
India	Cycle rickshaw	23	46
	Auto rickshaw	46	193
	Bus	1340	9400
Manila	Jeepney	273	1584

Sources: (6), (11), (16)

TABLE 8 Percent of Vehicle Ownership in Different Cities

Mode (City)	Owned by Driver	Rented by Driver	Others*
Auto rickshaw (India)#	34	51	15
Becak (Bandung)	18	82	0
Becak (Jakarta)	13	83	4
Cycle rickshaw (India)#	20	79	1
Jeepney (Manila)	9	71	20
Silor (Chiang Mai)	75	25	0
Samlor (Bangkok)	1	99	0

* = Drivers relatives, friends or employee-driven or cooperatives
# = The average values of 7 cities
Sources: (4), (6), (16), (17)

The only exception is found for Silor in Chiang Mai, where about 75 percent of drivers own their vehicles. In addition, the majority of owners have only small fleets (Table 9).

Fare System

In general, bus is the cheapest mode and taxi is the most expensive in all cities. The fares of paratransit modes are higher than bus because they provide convenient means of travel with a high frequency of service. The fare systems are classified into three groups: fixed, metered, and negotiated. Mostly, the fares of individual types of paratransit are decided through negotiation between passengers and drivers. In some countries, like India and Nepal, Auto Rickshaws are metered. But for shared or collective types of paratransit, fares are fixed. The Jeepney in Manila has the same fare system as that of the bus (Table 10).

In India, fare rates on Cycle Rickshaws and Auto Rickshaws are prescribed for typical journeys by the local authority. But in practice, all rates are decided by bargaining, even though Auto Rickshaws carry a meter. The fares per passenger kilometer of these two modes do not differ much, but the total fare paid per trip is higher on Auto Rickshaws because of the longer journey distance (Table 11).

The results of a 1990 survey of Samlor users in Bangkok shows that passengers believe the current fare bargaining system is not favorable to them. More than half of the Samlor passengers interviewed prefer a meter system or fare fixed by government (*4*). The recent introduction of metered taxi may reflect this view.

Operating Cost and Profitability

The exact earnings of paratransit drivers are difficult to determine. In Bangkok, the average operating revenue per day for Samlor is the

TABLE 9 Distribution of Owners' Fleet Size (Percent)

Mode (City)	Fleet Size 1	2	3	4	5-9	10-29	30+
Becak (Bandung)	0	0	----	--41-	-----	50	9
Bemo (Malang)	79	13	4	2	2	-----	Neg. ---
Jeepney (Manila)	55	15	7	4	-------	--19--	-----

Source: (2)

TABLE 10 Examples of Fare System in Different Cities

City	Mode	Fare System	Fares/Trip/Person
Bandung	Becak	B	Rp 50-100(3-6)
Bangkok	Silor	B	Baht 7(29)
	Samlor	B	Baht 10(41)
	Hired-Motor cycle	B	Baht 6.5(27)
	Pickup	F	Baht 2-7(8-29)
Chiang Mai	Samlor	B	Baht 2-3(8-12)
Dhaka	Auto rickshaw	B	
	Auto tempo	F	
	Misuk	B	
	Rickshaws	B	
Delhi	Auto rickshaw	B	
	Cycle rickshaw	B	
	Tonga	B	
Jakarta	Becak	B	Rp 76(4)
	Bemo	F	
	Bajaj	B	
	Opelet	F	
Karachi	Motor rickshaw	B	
	Tonga	B	
Nepal	Cycle rickshaw	B	
	Tempos	F	
	Meter tempo	B	
Manila	Jeepney	F	Pesos 0.25(1.2), 1st 5 Km, Pesos 0.05(0.22) additional Km.

Exchange rate: US1$ = Thai Baht 24.25
US1$ = Indonesian Rupiah 1865.38
US1$ = Indian Rupee 24
US1$ = Philippine Pesos 22.48
Notes: ( ) = The equivalents US Cent;
B = Bargained, F = Fixed
Sources: (2), (11), (17)

highest, and hired motorcycle is the lowest (Table 12). But their operating income, excluding personnel expenses, is almost the same. The fuel consumption of these paratransits is relatively low. For example, approximately 15 liters of fuel is required per shift (12 hr) for Samlor (*4*). The significantly low fuel consumption is due to the small size and less weight of vehicles (450 kg for Samlor) (*5*). Furthermore, comparing the average net pay, a driver earns the minimum labor wage of 90 baht in a shift (*4*), which is better than laborers on average.

The average daily revenue of the Jeepney driver in Manila was 397 pesos ($17.68) (Table 13). Daily expenses were 302 pesos ($13.45). Fuel/oil cost accounted for 53 percent of total daily expenses, whereas boundary fee (rent, repair, etc.) accounted for 44 percent and others (parking fee, dispatchers' fee, etc.) accounted for 3 percent of total expenses (*6*).

EFFECTS OF PARATRANSIT

Positive Effect

In the urban area, the transport sector including storage and/or communication provides large job opportunities for 2 to 20 percent of the total labor force. In India and Bangladesh the share of transport sector is remarkably high, 12 percent and 12.9 percent, respectively, because of the labor-intensive Cycle Rickshaw. About 10 percent of the total labor force in Manila was involved in the Jeepney services. This percentage was more in Chiang Mai and Bangkok, about 13 to 20 percent, in the minibus and Samlor services (*3*).

In Dhaka, about 380,000 people are directly employed as Rickshaw pullers, and another 80,000 are employed in ancillary services related to Rickshaws, together accounting for nearly one-fourth of

TABLE 11 Fare Structures of Paratransit Modes in India

Mode	Fare/Pax.Km (Paise)	Avg. Distance (Km)	Avg. Pax. /Trip	Fare/Trip (Paise)	Fare/Trip (US Cent)
Auto-rickshaw	45	4	1.9	342	14.25
Cycle-rickshaw	46	1.95	1.7	153	6.38

Source: (16)

TABLE 12 Financial Conditions of Paratransit Modes in Bangkok (Baht)

Items	Samlor	Silor	Hired-Motor cycle
Avg. Operating Revenue/Day	475.9	342.7	250.8
Ave. Operating Expenses/Day	319.8	194.1	112.3
Fuel Expenses	85.3	96.6	52.3
Others(Rental, Repair etc.)	217.4	137.3	66
Operating Income (Excluding Personnel Expenses)	138.1	148.6	138.5
Ditto(in US$)	5.69	6.12	5.7

Source: (11)

TABLE 13 Financial Profile of Jeepney Driver and Operator in Metro Manila

Items	Driver	Operator
Daily Avg. Revenue (Pesos)	397	133
Daily Avg. Expenses (Pesos)	302	46
Daily Net Income (Pesos)	95	87
Daily Net Income (US$)	4.23	3.87

Source: (6)

all employment in Dhaka. Motorized and nonmotorized public transport services together provided direct employment to 28,000 people in Patna, India, in the mid-1980s (*7*). Table 14 compares the generation of employment by different modes in Patna, India, which shows that paratransit accounts for the large share in providing employment for unskilled low-income workers.

Negative Effect

The accident rate of paratransits is often claimed to be excessive in developing countries. In Ankara (Turkey), 54 percent of all urban accidents involve a typical paratransit called Dolmus (*8*). Results of a passenger survey (1990) in Bangkok reveal that almost a quarter of the total 727 respondents had experienced accidents while riding on the hired motorcycles. Moreover, the traffic accident studies conducted in Thailand by the Department of Highways (1990) indicate that the ratio of accidents by hired motorcycles ranked highest, 25.6 and 21.8 percent in 1987 and 1988, respectively (*9*). Many accidents involving the paratransits occur as a result of sudden stops to pick up or set down passengers. Intense competition for passengers often gives rise to aggressive driving behavior, which in turn often leads to high accident rates.

The traffic mix of slow and fast vehicles is also another reason for accidents. In Dhaka, it was reported that the Rickshaw contributed to only 2.3 percent of traffic accidents compared with the motorized modes such as cars (45.5 percent), buses (21.5 percent), trucks (18.6 percent), Auto Rickshaws (5.9 percent), and motorcycles (5.5 percent) (*10*). But the actual number of accidents involving Rickshaws was unreported because of the illegal status of Rickshaws and lack of insurance claims.

The excessive working hours of paratransit drivers might be one cause for accidents. Controls on drivers' working hours are nonexistent or poorly enforced. For example, the average driver's working hours for Samlors, Silors, and hired motorcycles in Bangkok are, respectively, 10.7, 13.3, and 13.7 hr/day (*11*). In some cases drivers have to work even more than 15 hr/day to make a living or to keep their employment.

Other negative effects due to excessive numbers of small motorized paratransit vehicles are reduced vehicle speed and decreased road capacity due to indiscriminate stopping and starting. In Jakarta, Opelet routes overlapped with city bus routes result in an adverse effect on the free flow of traffic.

Table 15 shows the passenger car equivalent (PCE) of nonmotorized and motorized paratransits in Asian cities. The variances are related to data collection location (road links or intersections), vehicle size, and power-to-weight ratio. The PCE values are divided by the average occupancy of each paratransit to get the traffic impedance per passenger. In terms of road space use per passenger, a nonmotorized Rickshaw is about 10 to 20 times more inefficient than a bus and 5 to 15 times more inefficient than a minibus. Likewise, a motorized Auto Tempo and Auto Rickshaw show greater inefficiency compared with a bus or minibus.

For low-quality dual carriageway (width < 10 m) in Jakarta, when the proportion of Mikrolets increases from 10 to 25 percent, the traffic speed reduces from 16.2 km/hr to 6.7 km/hr for traffic volume of 1500 pcu/hr/lane. The Istanbul speed/flow relationship with Dolmus also obtained the same results as Jakarta (*12*).

Nonmotorized paratransit has the advantage over motorized from the viewpoint of pollutant emission. The principal pollutants by motorized vehicles include carbon monoxide (CO), nitrogen oxide (NO_x), hydrocarbon (HC), sulfur oxide (SO_x), and suspended particulate matter (SPM).

TABLE 14 Comparison of Employment Generation by Different Modes in India

Items	Public bus	Mini-bus	Auto-rickshaw	Cycle-rickshaw
No employees per Rs 10,000 investment	0.3	0.2	0.6	7.5
No. employees per 1000 pax. Kms/day	1.3-3.3	0.8-1.3	13-14	40-60

Source: (8)

TABLE 15 Passenger Car Equivalent (PCE) of Paratransits in Asian Cities

	Intersection			Road	
Mode	Dhaka	Calcutta	ESCAP	BRTA	Jakarta
Rickshaw (INP)	0.80	1.20	2.00	1.00	0.50
Auto Rickshaw (IMP)	0.50	–	1.00	0.75	0.80
Auto Tempo (SMP)	0.60	1.70	–	0.75	1.00
Mini Bus	2.00	1.00	1.00	3.00	2.60
Bus	2.50	1.50	3.00	3.00	3.30
Efficiency of Road Space Utilization (PCE/Passenger)					
Rickshaw (INP)	0.40	0.60	1.00	0.50	0.25
Auto Rickshaw (IMP)	0.25	–	0.50	0.27	0.40
Auto Tempo (SMP)	0.10	0.28	–	0.13	0.17
Mini Bus	0.08	0.04	0.04	0.12	0.10
Bus	0.04	0.02	0.05	0.05	0.05

BRTA=Bangladesh Road Transport Authority
INP=Individual Non-motorized Paratransit
IMP=Individual Motorized Paratransit
SMP=Shared Motorized Paratransit
Average occupancy: Rickshaw=2, Auto Rickshaw=2, Auto Tempo=6, Minibus=25, Bus=60
Source: (18)

Many cities of Southeast Asia exceed permissible limits of air pollutants set by the World Health Organization (WHO). For instance, WHO standards for SO_x (40–60 μg/m^3) are exceeded in Manila, 65 μg/m^3. SPM limits of WHO (60–90 μg/m^3) are exceeded by New Delhi (430 μg/m^3), Calcutta (400 μg/m^3), Jakarta (250 μg/m^3), and Bangkok (200 μg/m^3) (*18*). According to the USAID's study on environment of Bangkok (Table 16), major air pollutants increased significantly during the 1980s, and 1987 to 1989 levels are mostly exceeding the U.S. and Thai air quality standards.

Many motorized paratransit vehicles, such as Auto Rickshaw and Auto Tempo, are equipped with 2-stroke engines, which emit larger amounts of black smoke. In Dhaka, the proportion of such 2-stroke vehicles rose from 2.2 percent in 1982 to 1983 to 17.3 percent in 1988 to 1989, with increasing effects on the pollution problem. The Department of Environment (DOE) in Dhaka conducted a 10-day monitoring period in 1990, where 80 percent of Auto Tempo exceeded the DOE emission standard for black smoke (65 Hartridge smoke unit). A recent study (*18*) in the same city showed that the percentage of offenders against the black smoke standard of Auto Tempo and Auto Rickshaw was 80 and 90 percent, respectively.

ADMINISTRATIVE CHARACTERISTICS OF PARATRANSIT

In some countries, controls and regulations are introduced for maintaining smooth traffic flow and recently for environmental protection. Typical regulations include restriction of entry of new operators, restriction of paratransit operation in certain areas, control over financial liability requirements, and licensing of drivers. Recently in Nepal, the government banned the import of diesel engine Tempos for protecting the environment.

Restrictions on the total number of paratransit vehicles are usually imposed to protect bus operators, or to keep overcrowding at terminals and on the roads. For example, the Department of Land Transport (DLT) in Bangkok has set limits for the number of registered units of Samlor and Silor, 7,500 and 8,000, respectively (*11*). In Karachi, Auto Rickshaws were subjected to restrictions on new registrations from 1986 (*7*). In India, Indonesia, and Bangladesh, restrictions have been placed on the number of Cycle Rickshaw registrations. It is believed, however, that a large number of illegal paratransits are in operation in these cities.

TABLE 16 Levels of Air Pollutants in Bangkok, 1983–1989

			Ambient Standard	
Pollutant	1983-1986	1987-1989	Thai	US
Lead (μg/m^3)	0.1-1.0	0.6-5.45	10.0	1.5
Suspended Particulate (μg/m^3)	0.09-0.19	0.09-1.25	0.10	0.075
Carbon Monoxide (μg/m^3)	1.0-9.5	1.13-52.65	20.0	10.0

Source: (19)

Recently, the operation of nonmotorized paratransit was restricted to maintain smooth traffic flow in several areas of city. In Manila, tricycles have been banned from main roads and now operate mostly on smaller roads as feeder service. In Bangkok, Samlor, and Silor, they are not permitted to use expressways. In some cities without formal controls, paratransit operators' associations sometimes adopt a self-regulatory role to ensure that supply and demand are kept in balance.

FUTURE OF PARATRANSIT

In the future, urban rail systems may relieve the traffic congestion problems of developing countries. But this needs a huge amount of capital investment, which is almost impossible for most of the developing countries. In such circumstances, paratransit modes will continue their dominant role in the urban transport system. So it is necessary to undertake actions that will result in more effective use of paratransit and improved urban mobility. It will not be possible to withdraw nonmotorized transport from certain cities in the near future because of the economic and political effects this would have on employment. For such cities, it is necessary to separate nonmotorized traffic from fast traffic flows, and this can be achieved by creating physical barriers or providing individual lanes for nonmotorized transport, such as Becak lanes in Indonesia or Cycle Rickshaw lanes in India and Bangladesh. It would be better if these nonmotorized modes were restricted to feeder service only. Similar policy may also be applied for motorized paratransit.

Recently, metered taxis have been introduced in Bangkok. For individual types of paratransit, this is a better system. Reasonable and controlled fares for the rest of the paratransit modes should be provided. Furthermore, stands or terminals for paratransit vehicles would be useful to reduce hailing and stopping from nearly all points along the streets. Finally, to ensure passenger safety and comfort, and to maintain good appearance of vehicles, it is better to prepare certain minimum specified design standards, which include a shorter body for easier maneuvering in traffic and parking, engine types other than diesel powered, seating standards, and so forth.

CONCLUSIONS

The significant features of a paratransit system in the cities of developing countries are their flexibility and door-to-door service. Their popularity as public transport cannot be overlooked, as shown by the Metro Manila; it carries two-thirds of public-transport passengers. Certain physical and technical differences have been found in terms of passenger capacity, operating ranges, service-pattern, and regulatory frameworks. As a private business, the paratransit vehicles are managed and operated by small enterprises, which rent vehicles on a daily basis. They generate considerable employment opportunity and do not require significant public resources, a major attraction in developing countries with a shortage of funds.

Even in the future, the role of paratransit as a transport mode cannot be underestimated in the cities of developing countries, but unfortunately there is insufficient data in this field in many countries. So future joint survey and research will be important, and each government may provide a wide range of public transport modes with emphasis on paratransit systems.

REFERENCES

1. Vuchic, R. V. *Urban Public Transportation.* Prentice-Hall, Inc. Englewood Cliffs, N.J., 1981.
2. PADECO, *Non-Motorized Vehicles in Asian Cities, Part I. Inventory of Needs and Opportunities.* Draft Final Report, Prepared for World Bank, 1993.
3. ESCAP/UNCHS. *Study on the Role of Informal Paratransit in the Socio-Economic Development of Urban Areas.* Bangkok, Thailand, United Nations, 1987.
4. Agad, V. B. *Paratransit: Taxis and Tuk-Tuk in Bangkok.* AIT Thesis, Bangkok, Thailand, 1990.
5. Pholasith Tuk-Tuk Industry. *Thailand Tuk-Tuk Motorized Three-Wheeler.* Pamphlet, 1992.
6. Systems and Management Dynamics, Inc. *The Financial Assessment of Jeepney Operations in Metro Manila: Final Report.* Nov. 1985.
7. Replogle, M. *Bicycles and Cycle Rickshaws in Asian Cities: Issues and Strategies*, Institute for Transportation and Development Policy, 1992.
8. Fouracre, P. R. *Intermediate Public Transport in Developing Countries.* TRRL Laboratory Report 772, Crowthorne, U.K., 1986.
9. Tanaboriboon, Y. *Traffic and Public Transport in Bangkok.* Paper presented at the Infrastructure Development and Management Laboratory Seminar, University of Tokyo, 1992.
10. Islam, A. *The Role of Rickshaws in the Future Transportation System in the Dhaka Metropolitan Region, Bangladesh.* AIT Thesis, Bangkok, Thailand, 1990.
11. *The Study on Medium to Long Term Improvement/Management Plan of Road and Transport in Bangkok, Medium to Long Term Road Improvement Plan, Main Report*, Japan International Corporation Agency, 1990.
12. Mogridge, M. The Jakarta Traffic Management Study. 3. Impact of High Paratransit Flows. *Traffic Engineering and Control*, September, 1983.
13. Maunder, D. A. C., P. R. Fouracre, M. G. Pathak, and C. H. Rao. *Characteristics of Public Transport Demand in Indian Cities.* TRRL Laboratory Report 709, Crowthorne, U.K., 1981.
14. Soegijoko, B. C., and C. Horthy. Role of Nonmotorized Transport Modes in Indonesian Cities. In *Transportation Research Record 1294*, TRB, National Research Council, Washington, D.C., 1991.
15. Japan International Corporation Agency. *The Metro Manila Transportation Planning Study, Final Report*, Ministry of Transportation and Communications, Philippines, 1984.
16. Maunder, D. A. C., P. R. Fouracre, M. G. Pathak, and C. H. Rao. *Public Transport Supply in Indian Cities*, TRRL Laboratory Report 1018, Crowthorne, U.K., 1981.
17. Ocampo, R. B. *Low Cost Transport in Asia: A Comprehensive Report on Five Cities*, International Development Research Center, Ottawa, Ontario, Canada, 1982.
18. PPK Consultants Pty Ltd., *Greater Dhaka Metropolitan Area Integrated Transport Study (DITS)*, Working Paper No. 14, Prepared for Government of Bangladesh Planning Commission and Department of Economic and Social Development, United Nations Development Program, 1993.
19. Thailand Development Research Institute. *National Urban Development Policy Framework*, Bangkok, Thailand, 1991.

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Economics of Electric Trolley Coach Operation

E. L. TENNYSON

In 1995, pollution, congestion, urban viability and shrinking transit subsidies raise concerns for planners seeking alternative means of public transportation. Although the electric trolley coach alone cannot solve all or any of these problems, it may have the potential to mitigate some of them. Although the trolley coach emits no odors or particulates, it has not always been considered the most efficient means of public transportation. Over the past 40 years its use has declined by almost 93 percent, but the cost savings and revenue from modernization have never materialized on a per passenger basis. Its decline resulted in higher costs per passenger with less revenue. The use of simplistic cost-per-mile comparisons is partly to blame for the retrogression. A better cost measure is needed. Five North American transit systems still operate trolley coaches. Generally these are well-patronized systems. Their operating statistics are analyzed and compared with same-system diesel bus operations. It often appears that well-managed trolley coaches are moving people at lower costs on suitable routes than diesel buses and earn a higher revenue-to-cost ratio. The potential of increased revenue and ridership make trolley coaches worth reconsidering. Their advantages include traffic relief, stimulated economic activity, and reduced pollution. The up-front investment would be considerable and close management attention would be essential, but the adverse impact observed with its curtailment in the past suggests that a revival is worthy of study by many urban transit systems.

With the Clean Air Act amendments of 1990 mandating significant changes in transit bus propulsion and with cost control, revenue augmentation, and traffic congestion prime considerations, it may be useful to reexamine the trolley coach (trackless trolley) for urban transit application.

HISTORY

From 1934 to 1950 (excluding the war-rationed years of 1942 to 1945) electric trolley coach operation expanded from a fleet of 441 North American vehicles carrying 230,000 weekday passengers to almost 7,000 vehicles carrying six million weekday passengers. Diesel bus operations began about 1936, so it appears that management officials considered the trolley coach more economical than diesel buses for replacement of old, gasoline-powered buses and worn-out street railway lines. In a time when revenue per route was sufficient to earn a return on investment, streetcars continued to be employed as the most economical transit vehicle. About 6,000 new rail cars were ordered during this period (*1*).

Why were trolley coaches so popular during this period, and why have they become so unpopular since? At least four reasons can be given for the widespread use of trolley coaches during that 16-year period:

1. The electric power system required for trolley coaches resulted in a larger "rate base" than a diesel bus system would enjoy, making the electric operation more profitable under rate regulation. (The rate base is the active, used, and useful net investment in assets on which a profit was permitted to be earned. Rates charged by private transit companies were regulated by government authorities.)
2. The trolley coach had a superior power-to-weight ratio, which provided faster acceleration rates, particularly on hills. Brake wear was less with dynamic braking. Eight trolley coaches in rigorous service could do the same work on the same headway as nine diesel buses of equal capacity. A trolley coach might average 21.4 km/hr (13.3 mph) including stops, whereas a bus might average only 19.3 km/hr (12 mph) under the same conditions. On longer, less dense routes with fewer stops, the trolley coach lost some of its advantage.
3. Trolley coaches were usually 12.2 m (40 ft) long and 2.54 m (8.33 ft) wide, whereas internal combustion vehicles (buses) were limited by law to 10.7 m (35 ft) in length and 2.44 m in width, resulting in 10 fewer passengers per coach at the maximum load point, a difference of 18 percent. Labor cost per passenger was much less for trolley coaches.
4. The trolley coach contained nothing to freeze in winter, cost less to service and maintain, and was quiet and fume-free. However, weighed against the savings were added costs for power systems. Trolley coaches did not have to be fueled every day, however.

E. L. Tennyson 2233 Abbotsford Drive, RFD 55, Vienna, Va. 22181-3220.

Around 1949, laws governing motor vehicles were liberalized to permit 12.2-m (40-ft) diesel buses, but the 10.7-m (35-ft) bus bodies were too weak to be lengthened. The 12.2-m bus required a heavier body. More recent law revisions have allowed 2.6 m (8.5 ft) of body width.

Beginning in 1949 on the best transit systems, and before that on bus-only systems worn by war work, ridership declined as gasoline rationing ended and automobile manufacturing resumed, creating a surplus of transit vehicles and a shortage of cash. A few well-managed suburban systems, such as the Philadelphia Suburban Transportation Company and the city of Shaker Heights [Ohio] Department of Transportation, continued to sustain ridership with rail operation.

With the steady decline in transit revenue offset by continuing increases in cost, no new investment in fixed facilities was feasible other than for easily transferred buses on equipment trust certificates (mortgages). The rate base was no longer an issue, as the next week's payroll took top priority. Copper wires could be sold to raise cash, subject to reduced income tax rates. The trolley coach had lost two of its advantages, and private enterprise lost interest in the other two advantages, believing they were unachievable.

From 1950 to 1964, transit management officials had little opportunity to invest in future projects. Efforts were focused on survival, and often meant reduction in service (cost), increased fares, selling assets, and avoiding investment. Investment in trolley coaches was seldom considered, except in Philadelphia in 1954, when the city (not the transit company) purchased 43 Marmon-Herrington trolley

coaches to replace an aging outlying streetcar line in a growing area. The transit company leased the coaches at cost.

Management's ranks thinned as the industry shrank. Retiring professional engineers were seldom replaced. Trolley coaches were too much trouble to justify the effort involved in operating them, except in a few places, like Dayton, Ohio. Because the electric vehicles were limited to fixed routes (unless costly and complex supplementary power was added), they were not freely rerouted for one-way street plans or suburban expansion. They caused operating problems in emergencies and required more management attention. Trolley poles sometimes left the wire, causing minor (occasionally major) delays. In bad weather, trolley shoes had to be changed to avoid decimation. Overhead line crews were an added expense, and many residents objected to the overhead wires.

CASE FOR THE TROLLEY COACH'S RETURN

In view of this history, why consider trolley coaches again? It appears they have proven costly and obsolete. Conditions, however, have changed. The Urban Mass Transit Act now provides investment capital, if justified. The Clean Air Act amendments of 1990 prohibit the manufacture of diesel buses unless they are equipped with costly and heavy particulate traps or clean-fuel engines. Two-axle diesel and natural gas buses 12.2 m long are too heavy to comply with the weight limits necessitated by pavement destruction, catch basin collapse, and gas and water main damage. To maintain schedules, bus drivers must turn off air-conditioning when accelerating on hills, because it drains power from the engine. A greater problem arises at recovery time (layover) terminals where the engine must be turned off to comply with laws and community demands to mitigate pollution. When this is done, the bus quickly becomes unbearably hot and the windows are opened, rarely to be closed again until the bus is serviced. Today's bus patron expects an inside temperature of 76°F and is not interested in the problems involved in maintaining that temperature. Bus maintenance departments also encounter problems with the air-conditioning machinery.

Trolley coaches do not draw on the motors for their air-conditioning energy. The energy comes directly from the powerhouse and does not have to be turned off when climbing hills or idling. Power failures are also infrequent.

The increasing cost associated with diesel buses (greater weight, particulate traps or natural gas fuel, air conditioning, and the need for more powerful engines) has induced some transit authorities to reconsider trolley coaches. In cities such as San Francisco, Seattle, Washington, and Vancouver, British Columbia, the trolley coach never lost its appeal. These three cities are among the four highest in ridership per capita where rubber-tired vehicles are used (*2*). These systems have found that trolley coaches cost less to operate than diesel buses under similar conditions. The operational savings exceed the added cost of electric power (*3*). In these three cities and in Dayton, Ohio, transit management officials believe trolley coaches are worth the additional effort necessary to keep them running.

There is anecdotal evidence that passengers prefer well-managed trolley coaches, at least in favorable settings. About 40 years ago the Akron [Ohio] Transportation Company phased out its trolley coaches in favor of a revamped all-diesel bus operation. The company realigned its routes without fixed facility investment to improve service and reduce the number of bus-to-bus transfers required. A nationally known transit consulting firm was retained to help conduct origin-to-destination studies to ensure that the most efficient and effective plan was developed and installed.

After implementation of the "improved" service, almost one-fourth (25 percent) of the patronage was lost. The diesel buses had a negative effect. Old rider habits were hard to break and anticipated new riders were not interested. Roughly 16 to 18 percent of the loss was attributed to the frequent labor strife in Akron, fare increases, and the decline in ridership after World War II. However, the elimination of the trolley coach appears to account for the remaining 6 or 7 percent ridership loss (*4*).

The Denver [Colorado] Tramway Corporation had a similar experience about the same time. Its relatively new trolley coaches were replaced by through-routed diesel buses in what was described as a "more efficient" operating pattern. Riders avoided the new diesel buses in sufficient numbers to create an accelerated loss of ridership beyond what would be expected from the post-war trend (*5*).

More recently, Dayton attempted to eliminate trolley coaches against the wishes of some board members and many citizens. As the trolley coach operation shrank, so did patronage, despite an increase in service. Annual boardings dropped from 20.5 million in 1982 to 13.6 million in 1992, a loss of 34 percent. As trolley coach mileage shrank from 27 percent of the system to 10 percent, total kilometers operated increased by 31 percent. In nearby Cincinnati, Ohio, which had less service change, patronage declined by 19 percent with a service reduction of 14 percent (*6*). Public opposition in Dayton resulted in a change of management and a vote to restore the trolley coach system.

The new trolley coaches installed in Philadelphia in 1954 countered the trend of declining patronage. Because ridership required a 90-sec headway on the inner segment of the route, the city had the company install express wires to provide faster and less costly service for more passengers with the same number of coaches.

Even more recently, San Francisco, Seattle, and Vancouver have been expanding their trolley coach operations by replacing diesel buses on strategic routes. Toronto, however, has eliminated its trolley coach service despite public protest and favorable costs per bus hour (*7*). Ridership has fallen since the trolley coach service was terminated. Aging electrical equipment and high costs per vehicle kilometer were the factors cited for the decision. For example, during the phase-down sequence, trolley coach operations became much more costly per unit of service because of the loss of utilization.

COST PER KILOMETER OR COST PER HOUR?

Toronto's experience raises the question of cost per vehicle kilometer or cost per vehicle hour: which is more realistic or does it matter? Previously, most transit managers simplistically measured their economic performance in terms of cost per vehicle kilometer. Streetcars cost more because of track maintenance, and hence were eliminated in favor of smaller buses with lower costs per vehicle kilometer. However, the buses had lower carrying capacity and revenue potential. Although trolley coaches cost less per kilometer than rail cars, they now cost more per kilometer than diesel buses and have been eliminated except in certain transit systems where ridership is strong. Despite the higher cost per vehicle kilometer, trolley coaches often operate with a lower deficit and with a higher revenue-to-cost ratio. It was once thought that lowering the cost per kilometer without lowering revenue would reduce deficits. Unfortunately, this was not the case.

The experience of Youngstown, Ohio, which has 72 trolley coaches and 72 diesel buses, is illustrative. With trackless trolleys, the system was earning a 6 percent return on its investment as required by the franchise. Ridership and revenue were declining as

inflation forced fares higher and more commercial activities provided free parking. It was naively thought that substituting 43-cent/km (1956) diesel buses for 50-cent/km trolley coaches would not only preserve the enterprise, but also would result in a capital gain at a lower tax rate from the sale of the copper trolley wires. This was not to be. Since the trolley coaches were eliminated in 1957, ridership has fallen substantially. By 1958, the system fleet was reduced from 144 vehicles to 82 vehicles, all diesel buses. Ridership fell from 67,000 per weekday with trolley coaches to only 44,400 after a full year of diesel operation. A fare increase discouraged an estimated 10 percent of riders despite the efficiency of diesel buses. The secular trend of that time suggests that an additional 12 percent was lost. It appears that the loss of about 9 percent of the ridership was caused by the elimination of trolley coaches (*4*). This was worse than Akron's experience for lack of route improvements.

Because of the considerable investment required for its power system, the trolley coach's operation is limited to the busiest routes, whereas diesel buses can be used on both heavy and light routes. With more stops and traffic signals, the trolley coach averages 16 km/hr, including recovery time at terminals. With less traffic and fewer stops per kilometer, the typical diesel bus averages 19 km/hr (19 percent faster than the trolley coach). The diesel bus is not a faster vehicle in traffic, but enjoys more open road. Stopping for passengers and signals causes a loss of speed but is unavoidable, as passengers are the purpose of the operation. Trolley coaches average three stops per kilometer with 40 sec lost per stop, including the time for deceleration and acceleration, plus 1¼ min/km (48 km/hr). Excluding recovery time, this averages 3.3 min/km or 18 km/hr.

Diesel buses on longer, less dense routes average only 2.2 stops per kilometer at 45 sec each (fewer doors and less acceleration), so only 2.9 min are consumed per kilometer, which is 21 km/hr. Actual speeds will vary with the route, but the difference is the issue.

Despite the frequent use of mileage as a cost analysis tool, most transit operating expenses are not related directly to distance. There are six primary categories of transit costs, none of which is directly related to distance. Almost half the total costs are salaries for the driver and his or her supervisors (including fringe benefits). Almost universally, drivers in urban service are paid by the hour, not by the kilometer. Assuming a $15/hr basic wage for 1995, with 40 percent fringe benefits it costs $1.30/km to pay the driver on a 16-km/hr schedule including recovery time, compared with only $1.09/hr on a 19-km/hr schedule. Whether diesel buses or trolley coaches are used is not important. That is where Youngstown and others erred. By looking only at cost per kilometer, they saw an 8 percent overall savings (16 percent on drivers alone) that was not there when diesel buses were assigned to slower, heavier routes.

OTHER COST FACTORS

Physical plant maintenance is only partially related to vehicle kilometers or hours. Trolley wire and hardware become worn in direct proportion to vehicle passes, or kilometers, but the wages and fringe benefits of overhead line men, and the maintenance costs for substations, span wires, feeder cables, accidents, weather adjustments, and rerouting are more significant and not related to vehicle kilometers. Length of wire is a more common denominator. Trolley wire and substations cost $4,800/year per route kilometer for maintenance, or $3,100/km plus 1.5 cents per vehicle kilometer. Economy is enhanced where travel is dense or more than one route uses the same wires.

Garage costs are determined by fleet size and length of wire in the yard, where applicable. Low utilization, peak-only suburban service requires as much garage space as busy all-day vehicles with high use.

Maintenance of vehicles is more proportional to the number of accelerations and decelerations than the number of kilometers traveled, except for tire rental, which is only 2 percent of the cost. Tire rental can be computed separately.

Air-conditioned, reclining-seat, lavatory-equipped intercity buses cost less per kilometer to maintain, even with three axles, than spartan urban buses. By the bus hour, however, intercity buses cost more.

In the nation's capital, the Washington Metropolitan Area Transit Authority must keep detailed records to bill two adjoining states (Maryland and Virginia) and the District of Columbia separately for specific services rendered. These records confirm that the number of mechanics per thousand vehicle kilometers is much less in the inner city (16 km/hr) than in the suburbs (22-1/2 km/hr). Despite the lower number of mechanics in the city, the distance between failures is seldom up to 3,200 km, compared with more than 6,400 km in Virginia, which has more mechanics per bus. All of the Washington, D.C. buses are maintained at the same central overhaul shop, and many are old (*8*).

Accelerations cause wear on a vehicle's drivetrain, and decelerations wear out the brakes. Cruising on a suburban freeway is much less mechanically costly, despite the rapid accumulation of kilometers. Bus hours are a much more accurate denominator of vehicle maintenance cost, which averages 75 cents/km at 16 km/hr, but only 62 cents/km at 19 km/hr. Youngstown experienced a 17 percent savings on maintenance by replacing trolley coaches with diesel buses, but the savings evaporated when diesel buses were used for busy routes.

Energy consumption offers an excellent example of the error of using kilometers to estimate fuel cost. J. Northcutt reported that for the Cincinnati Transit Company (now known as the Southwestern Ohio Regional Transportation Authority) careful measurement on four routes (two diesel and two trolley coach and two hilly and two level) found energy consumption more proportional to hours than kilometers. Diesel buses continue to consume fuel when stopped, but electric buses do not. Cincinnati found that more than two-thirds of the energy cost was proportional to time and less than one-third to distance. Because trolley coaches accelerate faster, they consume more energy in that phase, but will coast more at speed. The added energy for acceleration is justified by reduced vehicle hours and added ridership, as well as by maintenance savings.

Precise energy consumption measurements on Philadelphia MP-85 commuter cars (Silverliner II and III) determined that these electric vehicles consumed 220 kW·h of power per scheduled vehicle hour at any speed. In local service at a 32 km/hr average with 0.8 km station spacing, power consumption was 7 kW·hr per car kilometer, but at a 97-km/hr average (28 km between stops) it was only 2.3 kW·hr/km, a perfect correlation with hours but none at all with distance (*9*).

Casualty and insurance costs are not related to hours or kilometers. They are incurred by passenger mishaps and traffic conflicts. A bus kilometer on a suburban freeway with 3½ m lane widths will be almost accident-free, but a bus kilometer on congested, narrow, signalized streets with passengers boarding and alighting will be accident-prone. For lack of a better correlation, one-third of casualty costs will be related to passengers, one-third to bus hours, and one-third to kilometers to reflect traffic exposure. Routes selected for trolley coach operation will be a much higher accident risk than outlying diesel bus routes. On the same street there should be no

difference. Trucks touching overhead wires may be a nuisance, but circuit breakers immediately shut off power. Diesel buses carry hazardous fuel that causes toxic exhaust.

General and administrative costs are difficult to assign meaningfully. Some properties assign them by revenue to make busy routes help carry poor routes. Youngstown loaded trolley coach costs in this way. Other properties assign general and administrative costs in proportion to other costs, again favoring diesel buses if costs are distance-based. In Youngstown all income taxes were charged to trolley coaches since diesels operated at a loss. Income taxes are no longer a transit problem, but they illustrate the cost allocation problem.

Since there is no obvious common denominator for general and administrative costs, one-third may best be apportioned by revenue as a surrogate for passengers carried; one-third in proportion to vehicle hours for operational relationship; and one-third in proportion to all other costs as a reflection of where effort is being directed. Some analysts omit general and administrative costs from comparisons, but this risks the omission of relevant costs.

ELECTRIFICATION INVESTMENT

The electrification system for trolley coaches is capital intensive, although much less so than for a rail system. One million dollars for 1.61 km (1 mi) is a probable cost in 1995, if excessive design and hardware costs are avoided (see Table 1). Garage costs for trolley coaches can be less. No fueling facilities are required, nor do coaches need to be stored inside or heated all night in cold climates. This may save up to $125,000 per trolley coach on garage facilities. Air pollution controls will also cost less, with substantial savings described in the following sections.

In addition to the operational savings described previously, trolley coaches reduce environmental clean-up costs and have a minor impact on highway costs by increasing transit usage. There are no fuel spills or leaking tanks to clean up, nor is there any increase in local air pollution. If coal or oil is used for power generation, there is effluent comparable with the pollution emanating from oil refineries, but the transit vehicle is more fuel-efficient on busy routes. With natural gas or water power, the trolley coach involves no air pollution, nor does it contribute to noise pollution.

A diesel bus averages 42,580 L of fuel consumption per vehicle per year, resulting in almost 1 Mg of nitrous oxide, particulates, and volatile organic compounds. The practical cost of mitigating air pollution is approximately $2,250/Mg. Much higher costs are possible, but they can be avoided by alternative solutions (*10*).

On a busy downtown street with 120 buses per peak hour in both directions, the pall and odor of diesel bus exhaust is as noticeable as it is offensive and costly to alleviate. Pedestrians, including motorists who have parked, are loath to breathe the offensive air and may take their activity elsewhere. Some are allergic to diesel fumes. With trolley coaches, these problems are avoided. Concerns over electromagnetic effects have been relieved by studies that have proven electric vehicles to be no more dangerous than common household appliances (*11*).

TABLE 1 Trolley Coach Power Supply Investment: 1995 Estimate

ELEMENT	Dollars per Two-way Kilometer
Substations - 60 kw / coach, 1 coach / km.	$ 247,000
Trolley Contact Wire, 2/0 grooved (a)	15,500
Power Feeder Cble - 500 cm (a)	20,200
Span Wires - 44 spans	1,500
Hardware - 360 pieces per km.	18,600
Line Poles - 44 (assume 43 more joint use)	43,000
Feeder Insulators - 93	6,200
Special Work (Trolley frogs, etc)	18,600
Installation Labor - 410 hours, force account	24,800
Engineering at ten percent	39,600
Contingencies at 15 percent	65,000
MINIMUM TOTAL for ONE TANGENT KILOMETER	$ 500,000
Additional investment for heavier traffic density, curves, no shared line poles, and unusual situations	$ 125,000
AVERAGE TOTAL per two-way route kilometer	$ 625,000
AVERAGE TOTAL for One Mile	$ 1,000,000

(a) = Copper and phosphor-bronze metal prices are subject to considerable fluctuation and may vary considerably, year to year.

SOURCE: H.S. Zwilling, and Harrison; Design of Catenary Systems Transportation Research Board, Specialty Conference, Pittsburgh, Penna. 1985. page 21, adjusted to 1995.

REVENUE

Passenger revenue is also a factor in public transit economics. It is not fixed or inelastic, particularly among choice riders. The quality of transit service will have some impact on revenue. Studies in Philadelphia and St. Louis, Missouri, found that transit patronage increased by 3 percent for each minute of travel time saved (*12*). Because trolley coaches accelerate faster than diesel buses and load more quickly with double-front doors, there is the possibility of saving 11 percent of the running time. Traffic problems restrict free-running operation, so only one-half of the potential is likely. A 3 percent gain in revenue is almost certain. The fixed routes and absence of fumes may also contribute to increased ridership. Overall, trolley coaches should attract at least 5 percent more passengers than diesel buses on the same route and schedule. As noted previously, conversion from trolley coach to diesel operation has usually been accompanied with rider loss. Dayton gained only 22.5 percent in revenue from a fare increase of 84.5 percent, whereas costs increased 102.5 percent from 1982 to 1992 as diesel buses replaced trolley coaches (*13*).

Based on the information in this study, it appears that trolley coaches generate up to $4,000 more revenue per year than diesel buses on the same route and schedule.

REAL-TIME COSTS

The matrix of unit costs shown in Table 2 has been compiled from actual operating results in Dayton, Philadelphia, San Francisco, and Seattle. In Table 3, Vancouver is compared with Toronto when it had more trolley coach operation in 1987. The data is adjusted to reflect $15/hr basic wages to avoid distortion by varying wage rates. Some large systems have higher wages than $15/hr. Fringe benefits are actual values.

San Francisco power costs are excluded from the cost data because the power there is not bought at market rates. Amortization assumes a trolley coach density of one coach per directional kilometer, or two coaches per route kilometer with salvage value deducted. Actual costs will vary inversely, proportional to service density. For routes with electrification in place, amortization will be greatly reduced.

CONCLUSION

Although trolley coaches (trackless trolleys) cannot be economical on most transit routes, they can be economical and effective on relatively busy bus routes less subject to rerouting because they are in mature areas. Light-rail transit may sometimes be more economical and efficient on the busiest routes, but a significant percentage of passengers can be well-served by trolley coach operation. Depending on the route pattern and the length of common or joint route overlap under common wires, trolley coaches can be economical for routes with at least 6,000 weekday passengers (*15*). When travel volume exceeds 20,000 weekday passengers per route, light rail should be considered if its installation is practical. When light rail is impractical, trolley coaches should be considered for up to 25,000 weekday passengers. For more than 25,000 weekday passengers, some form of rail transit should be devised.

Each route requires unique analysis. System standardization should not be more important than operating economy and ridership maximization. Air pollution control, revenue optimization, operational economy, passenger attraction, and traffic relief all must be given serious consideration before capital is invested in transit rolling stock. The Clean Air Act amendments of 1990 and the Intermodal Surface Transportation Efficiency Act have made these considerations a priority in an effort to persuade motorists to switch to public transit.

TABLE 2 Operating and Maintenance Cost Comparison: 1992

	COST per VEHICLE HOUR (14)	
COST or REVENUE ELEMENT - 1992	DIESEL BUSES	TROLLEY COACHES
Maintenance of Physical Plant	$ 3.95	$ 5.06
Maintenance of Vehicles	12.42	9.91
Fuel or Power (excl. San Francisco)	2.43	2.61
Conducting Transportation	32.28	32.28
Casualty and Insurance	2.28	1.96
General and Administrative	10.89	8.18
TOTAL COST per VEHICLE HOUR	$ 64.25	$ 60.00
Passenger Revenue from Operations	23.04	24.40
NET COST per VEHICLE HOUR	41.21	35.60
Revenue to Cost Ratio	36 %	41 %
Estimated Pollution Abatement Cost	$ 0.83	0
Amortization of Investment	13.00	$ 19.00
GROSS COST per VEHICLE HOUR	78.08	79.00
NET COST per VEHICLE HOUR	$ 55.04	$ 54.60

TABLE 3 Dayton and Canadian Trolley Coach Operating Results: 1987

COST CATEGORY	COST per COACH HOUR BUS DAYTON	TROLLEY	BUS TORONTO[c]	TROLLEY	BUS VANCOUVER[c]	TROLLEY
Plant Maintenance	$ 2.09	$ 6.10	$ 1.61	$ 4.80	$ 0.00[d]	$ 0.53
Vehicle Maint'nce	8.45	8.44	9.18	10.14	10.61	10.00
Fuel or Power	2.34	2.62	4.10	2.00	5.00	2.00
Transportation	25.43	20.45[a]	27.46	28.18	29.82	29.82
Casualty Costs	1.18	1.03	1.20	1.24	1.42	1.33
General and Administrative	7.29	5.36	6.73	7.36	7.40	6.32
1987 TOTAL	$ 46.78	$ 44.00	$ 50.28	$ 53.72	$ 54.25	$ 50.00
Annual Fare Revenue	$ 7.38	$ 11.04	$ 27.34	$ 33.91	$ 25.59	$ 28.08
NET COST / BUS HR.	$39.40	$ 32.96	$ 22.94	$ 19.81	$ 28.66	$ 21.92
REVENUE-COST RATIO	16 %	25 %	54 %	63 %	47 %	56 %
POLLUTION COST[b]	$ 0.83	o	$ 0.83	o	$ 0.83	o
PLANT INVESTMENT	$ 13.00	$ 19.00	$ 13.00	$ 19.00	$ 13.00	$ 19.00
GROSS COST / HR.	$ 60.61	$ 63.00	$ 64.11	$ 72.72	$ 68.08	$ 69.00
NET COST Per HOUR	$ 53.23	$ 51.96	$ 36.27	$ 38.84	$ 42.49	$ 40.93

(a) = indicates the reported expenditure was inordinately low - 25 percent has been added.
(b) = indicates the frugal cost of mitigating a megagram (0.9 ton) of air pollution per bus per year. See reference (10).
(c) = Neither Toronto nor Vancouver reported all details available in Section 15 reporting. Interpolation has been utilized to estimate the sub-items. The totals are as reported and not estimated.
(d) = Garage fixed facility costs are included in Vehicle Maintenance.
Both Dayton and Toronto were planning to phase out trolley coaches in 1987.

Successful trolley coach systems require more effort at the management level, but in appropriate cases are well worth the additional time and energy to operate them.

REFERENCES

1. *American Transit Association Fact Book for 1950*, New York, N.Y.
2. U.S. Department of Transportation, Mass Transit Statistics Section 15 for 1992. Federal Transit Administration, Washington, D.C., Table 21; and *Operating and Financial Report for 1990.* Canada American Public Transit Association Washington, D.C.
3. U.S. Department of Transportation. Mass Transit Statistics Section 15 for 1992, Table 10. Federal Transit Administration, Washington, D.C.; and American Public Transit Association. *Proc. Rail Transit Conference.* Vancouver, B.C., Canada, June 1990.
4. United Transit Company and Youngstown Municipal Railway. *Annual Report 1957 and Monthly Reports to the City of Youngstown, Ohio*, 1951–1956.
5. Moody's Investment Services. *Moody's Transportation Manual.* Denver Tramway Corporation, 1960.
6. U.S. Department of Transportation. *Mass Transit Statistics Section 15 for 1982 and 1992, Table 21.* Federal Transit Administration, Washington, D.C.
7. American Public Transit Association. *Passenger Transport*, Jan. 1994, Washington, D.C.
8. Washington Metropolitan Area Transit Authority. *General Manager's Budget*, Washington, D.C., 1992.
9. City of Philadelphia. *Specifications for Electric Multiple Unit Passenger Rail Cars 1962 and 1966.* Philadelphia, Penna.
10. Metropolitan Washington Council of Governments. *Transportation Control Measures Analyzed for 15 Percent Rate of Progress Plan*, July 1994, p. 26, Section 5—Methodology, Washington, D.C.
11. Papers presented at Session 155B, 1993 Annual Meeting of the Transportation Research Board, Washington, D.C.
12. Penn Jersey Transportation Study. *The State of the Region, 1964*; and St. Louis Public Service Company Research Department, St. Louis, Mo.
13. U.S. Department of Transportation. *Mass Transit Statistics Section 15 for 1982 and 1992, Table 1.* Federal Transit Administration, Washington, D.C.
14. U.S. Department of Transportation. *Mass Transit Statistics Section 15 for 1992, Tables 10 and 11.* Federal Transit Administration, Washington, D.C.
15. U.S. Department of Transportation. *Mass Transit Statistics Section 15 for 1991 and 1992, Table 16.* Federal Transit Administration, Washington D.C.

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Evaluation of Visual Impacts of Trolleybus Overhead Catenary System Intersections

ARTHUR SCHWARTZ, JOHN S. KULPA, AND JOHN C. FALCOCCHIO

This paper presents an approach to evaluating the visual impact of trolleybus overhead catenary system (OCS) intersections based on the quantity of special work hardware required to construct the intersection. Examples of various intersection types are presented using both diagrams and photographs, and a scoring system is developed. The scoring system is used to rank common intersection types and produce a scale of visual impact that can be used to evaluate unique intersection configurations. The effect of street width on the visual impact of intersections is discussed, as is the related effect of advance turn lanes. Approaches to reducing visual impact by changing intersection layout are illustrated and their effect on bus operations is discussed.

A method for evaluating the visual impact of intersections in trolleybus systems is presented in this paper. This approach can be used with the illustrations in this document to evaluate the most commonly used intersection types. It can also be applied to evaluate the visual impact of trolleybus overhead catenary system (OCS) intersections that are designed to fit unique street and bus movement patterns.

TROLLEYBUS OPERATIONS AND SYSTEM DESIGN

Although the general structure of transit routes is defined by the demand for service, there are many other factors that can influence route location at the specific street or intersection level. Among these are the feasibility of street use, turning movements, and environmental concerns such as noise. In the case of trolleybus routes, an additional factor (often replacing other environmental concerns) is the visual impact of the OCS. There are numerous opportunities to reduce visual impact by subtle changes in route design that have little or no impact on service to the public. Many of these will affect such elements as turnback loops, garage routes, and emergency detour capability that are largely invisible to the transit user.

The goal in trolleybus system design should be to avoid the use of system elements that are visually obtrusive. In general, special work (switches, crossovers, and curve segments) is more obtrusive than straight trolley wire. Use of these components should be avoided or minimized when feasible to do so without significantly affecting operations.

The first step in designing OCS for trolleybuses is to determine the amount of wire and special work that is actually needed. This requires the preparation of a system wire map showing revenue routes with scheduled turnbacks as well as garage access routes. Garage access routes must take into account both minimizing running time and minimizing the amount of nonrevenue wire.

A. Schwartz, Arthur Schwartz Associates. J. S. Kulpa and J. C. Falcocchio, Urbitran Associates, Inc., 71 West 23rd Street, New York, N.Y. 10010. Present address for J.S. Kulpa is Korve Engineering, 201 South Lake Avenue, Suite 706, Pasadena, Calif. 91101.

Any new system is likely to use vehicles with some auxiliary power capability. The simplest auxiliary power system using batteries is sufficient to eliminate the need for most of the wire found on existing systems that is not regularly used. This includes both wire and special work used only in emergencies and wire used infrequently on a scheduled basis. APU use will require additional stops for removing and replacing poles. Thus, frequent use in revenue service will substantially degrade travel time.

Emergency wire is most often provided in downtown areas, where a street closure will affect multiple routes. Most transit systems that use trolleybuses have a sufficient number of spare diesel buses to substitute for trolleybuses on one route, but can only schedule multiple route substitutions on weekends or late evenings.

Figure 1 shows an OCS design in an area of downtown Seattle. The wire that is used for scheduled service, including garage movements, is differentiated from the wire needed only in emergencies. It can be observed that one intersection and two blocks of wire could be eliminated with APU availability and that the two most complex intersections would each require less than half the special work than is used in the current design.

Another means of reducing the amount of wire and special work is to review the regular route operation to determine if there are any route variations that operate infrequently and could be handled by rescheduling or with the APU. For example, there may be two short turn locations that are used at different times of day that could be combined into a single location. Another example is a situation in which a few late evening trips operate over both branches of a route that is otherwise scheduled with alternate trips on each branch. Here, the APU could be used for the turn connecting the branches.

INTERSECTION EVALUATION

Although the appearance of an intersection is influenced by several factors, including street width and the placement of special work within the intersection, the most important factor is the amount of special work in the design. In particular, complex intersections, or intersections requiring a large number of special work components, can be visually overpowering.

In order to evaluate the visual impact of trolleybus OCS intersections, it is first necessary to develop a rating scale. The rating scale proposed is based on a count of the number of special work components used in the intersection. For this purpose, a weighted count is used, with switches and crossovers having a weight of 1 and curve segments having a weight of ½.

This weighting was selected because a curve segment is basically a flat plane object visually, and thus has significantly less impact from the motorist's or pedestrian's perspective than does a switch or crossover. These elements contain section insulators, jumpers,

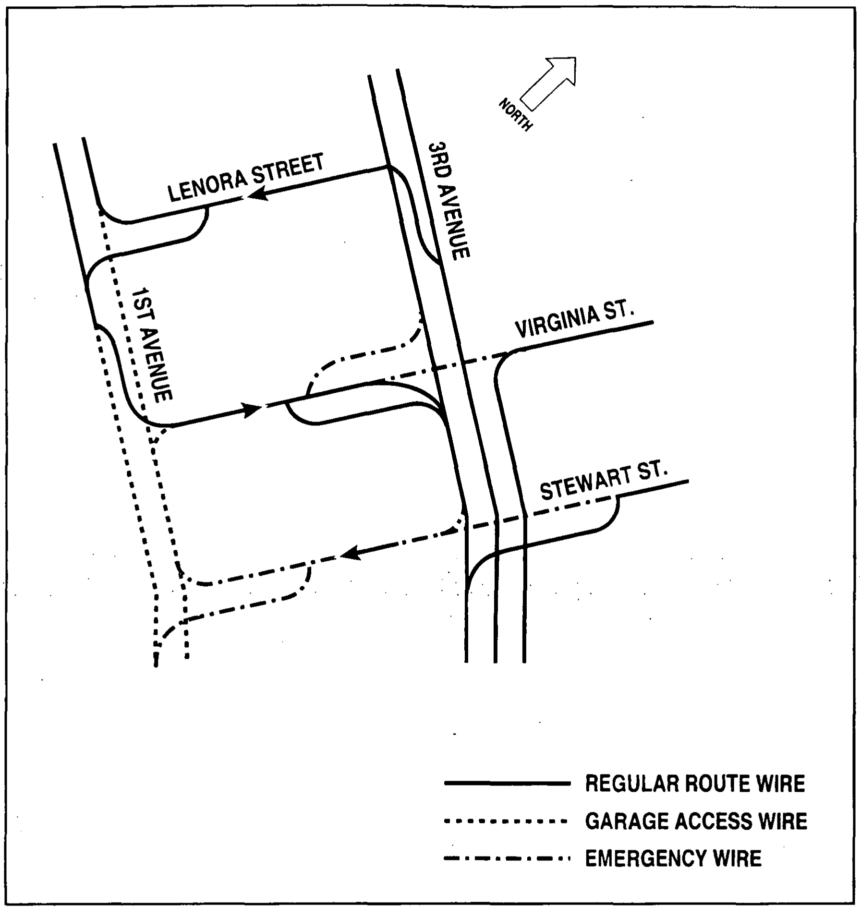

FIGURE 1 Regular route, garage access and emergency wire, north end of Seattle CBD.

and switch-operating hardware that protrude a noticeable distance above the plane of the wire and thus make the element more visible at the usual shallow view angle. In plane view, a switch, crossover, or curve segment all appear to have about the same visual mass.

As previously noted, this analysis is most useful for the more complex type of intersection. A system with dense route grid, such as San Francisco or Vancouver, will have a large number of complex intersections. A system that is primarily radial will have not only fewer intersections, but most of these will be relatively simple types. For example, Seattle, which is a combination of a radial and a grid system, has 96 intersections with switches or crossovers. Sixty-three of these intersections are simple, while 33 are complex.

A simple intersection is one that has a visual impact rating of 5 or less. Examples include a right turn into a turnback loop, with a visual impact rating of 2; a left turn in the same situation, with a visual impact rating of 4; a crossing of two routes without turns, with a visual impact rating of 4; and a turn combined with a transition between one-way and two-way operation with a visual impact rating of 5. This last configuration is shown on the right and left sides of Figure 2 below.

Figure 2 presents plans for several types of complex intersections. These are:

1. Diverging route;
2. Half wye;
3. Crossing with one pair of turns;
4. Full wye;
5. Crossing with two pairs of turns (1/2 grand union); and
6. Crossing with all possible turns (grand union).

Photographs of the first five types are shown in Figures 3 to 7. No complete grand union exists in the United States or Canada, so that it is included as a theoretical worst case.

Table 1 gives the number of special work elements used in each type of intersection and gives a visual impact rating for each type.

The complex intersection types shown in Figure 2 are shown because, except for Type 6, these tend to be commonly used configurations. For example, in Seattle, 25 of the 43 complex intersections are represented by Types 1 to 5, with 18 being Type 1 or Type 2.

Intersections similar to the first two types, with visual impact ratings in the range of 6 to 8, appear to be suitable for use at any location. Intersections similar to the second two types, with visual impact ratings in the range of 9 to 15, may be used in most locations but should be avoided in the most visually sensitive areas if feasible. Intersections with visual impact ratings of greater than 15 should be avoided unless there is no feasible alternative.

This approach will be useful not only in evaluating the visual impact of the common intersection types described above but also for assessing the visual impact of unique intersection designs. Figures 8 and 9 show two unique intersection types. In Figure 8, a crossing with one pair of turns is modified to include a four-wire local and express-wire layout on one of the streets. The effect is to

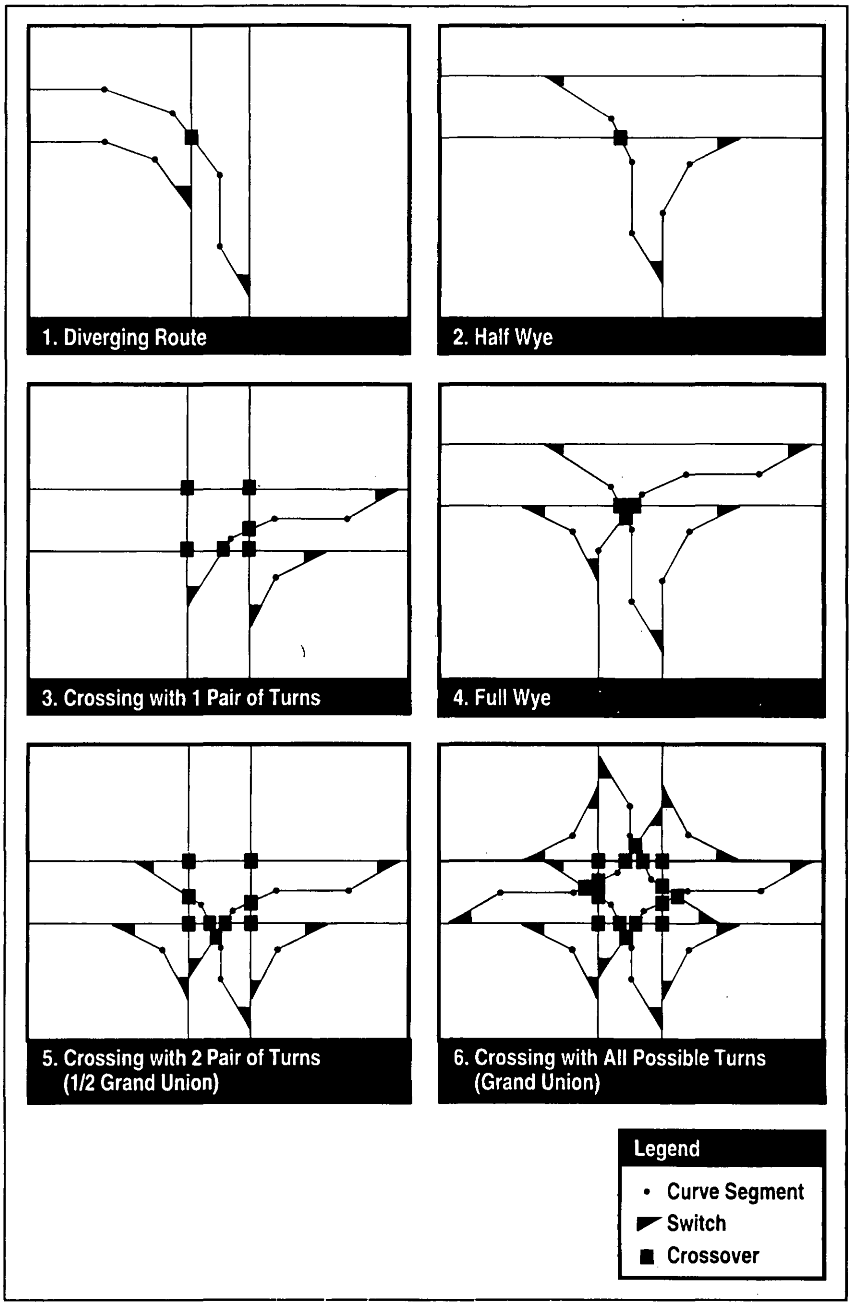

FIGURE 2 Intersection types.

TABLE 1 Visual Impact Rating of Intersection Types

Type	Switches	Crossovers	Curve Segments	Visual Impact Rating
1.	2	1	6	6
2.	3	1	5	6.5
3.	4	6	4	12
4.	6	3	10	14
5.	8	9	8	21
6.	16	16	16	40

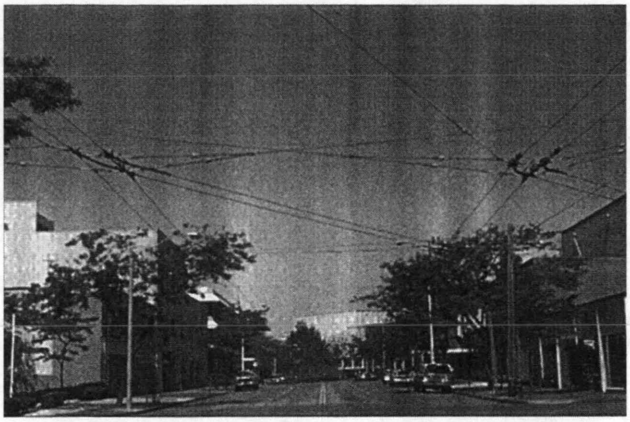

FIGURE 3 Diverging route, Third Ave. and Cedar St., Seattle (Type 1—visual impact rating: 6). Note directional control contractors ahead of facing switch.

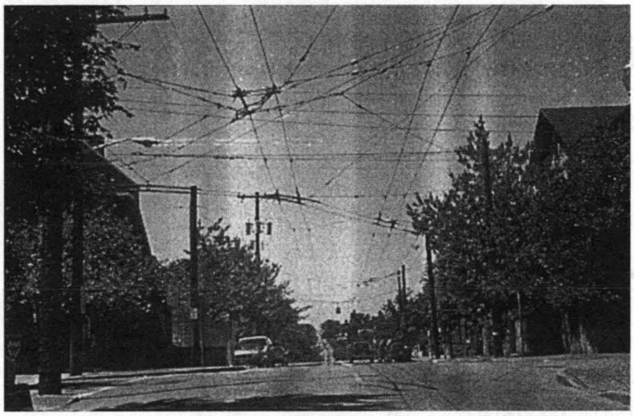

FIGURE 4 Half wye, 33rd Ave. and E. Union St., Seattle (Type 2—visual impact rating: 6.5).

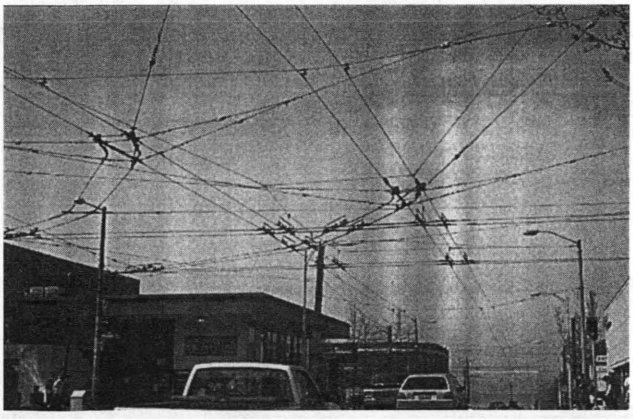

FIGURE 5 Crossing with one pair of turns, Broadway and John St., Seattle (Type 3—visual impact rating: 12).

FIGURE 6 Full wye, Queen Anne Ave. and Boston St., Seattle (Type 4—visual impact rating: 14). Note inductive antenna and the control cable and box on pole at right.

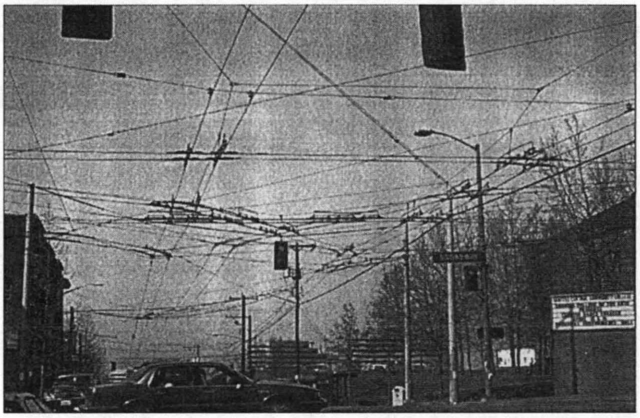

FIGURE 7 Crossing with two pairs of turns (1/2 grand union), Broadway and Pine St., Seattle (Type 5—visual impact rating: 21).

increase the number of crossovers from 6 to 12 and raise the visual impact rating from 12 to 18.

Figure 9 shows a two-way diagonal street crossing a one-way street grid. This intersection requires eight switches, seven crossovers, and only three curve segments for a visual impact rating of 16.5. Even with this level of complexity, only five of eight possible turn movements are included. This figure also shows that there are situations in which turns of 60 degrees or less can be installed without the use of curve segments.

ADDITIONAL CONSIDERATIONS IN INTERSECTION DESIGN

One approach to reducing special work concentration is to utilize one-way operation, both for route location in dense areas and for garage access. The use of separate streets for garage entry and exit will result in two intersections, each with around half the visual impact of a single intersection used for both entrance and exit routes.

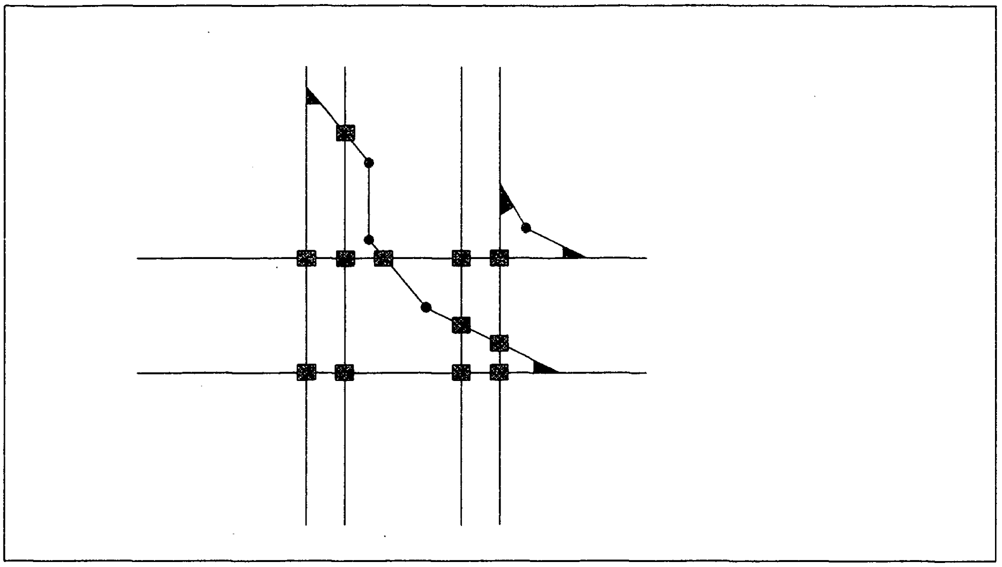

FIGURE 8 Crossing with one pair of turns with four-wire street.

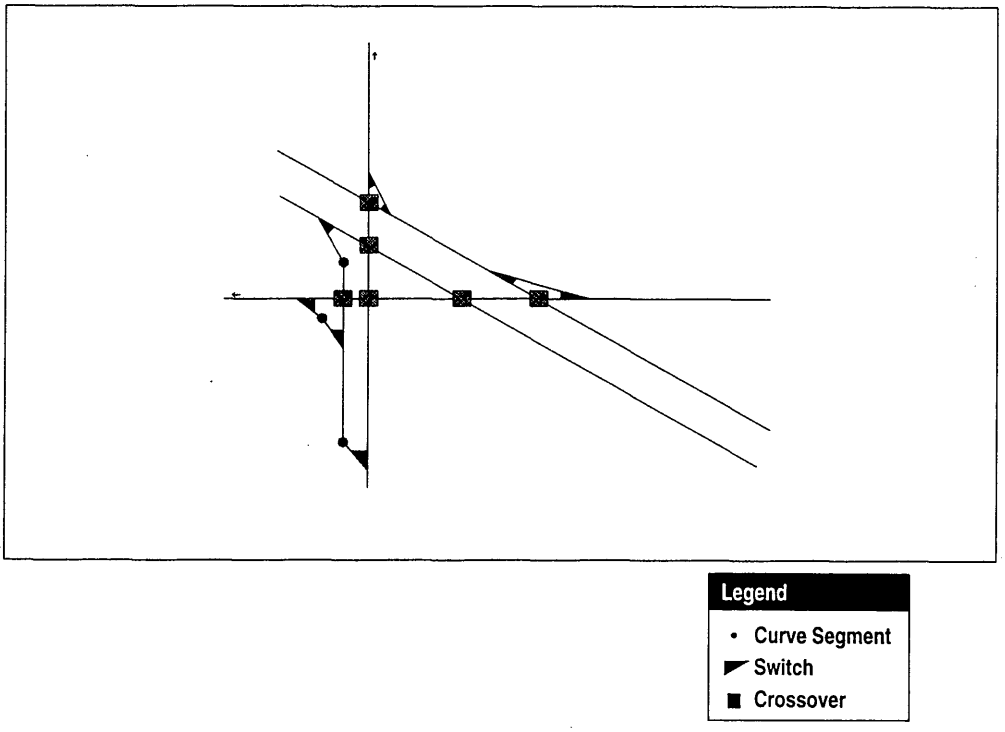

FIGURE 9 Two-way diagonal street crossing; one-way street grid.

One-way operation on parallel streets is often feasible in downtown areas, even though the streets are used for two-way traffic. Even when a single "Main Street" is used by many transit routes, the intersection streets are often appropriate for one-way operation.

For example, an intersection of two streets with one-way wire with both turns, as shown in Figure 10, has a visual impact rating of 7. Four such intersections replace the grand union of Figure 2, which has an impact rating of 40. Even when bus movement is concentrated on two intersecting streets, the use of a parallel street and the dispersal of turn movements will reduce the impact of special work substantially. The layout shown in Figure 11 uses four intersections with impact ratings between 5 and 7 to provide the capability for all possible movements.

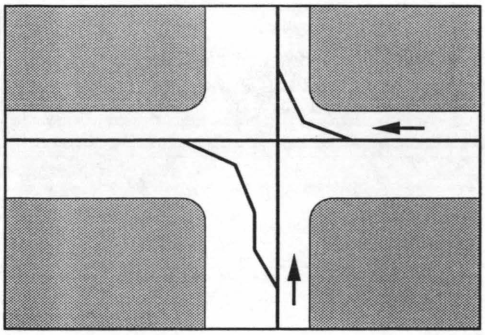

FIGURE 10 Intersection of two streets with one-way wire and both turns.

On streets with two-way wire, right turns produce less visual impact than left turns in that crossovers are not needed and the special work is kept out of the center of the intersection. Thus, where feasible, a right turn should be used rather than a left turn to provide the same movement capability.

Street width will also affect the visual impact of intersections. Straight wire is usually designed with the negative (curb-side) wire between 9 and 14 ft from the curb, depending on parking regulations and system preference, thus establishing the location of intersection approaches. Thus, the spacing of special work elements will vary depending on street width. Figure 12 shows a diverging route on a narrow street. The same configuration on a much wider street is shown in Figure 4.

Advance turn lanes can have either a positive or negative impact on the appearance of an intersection. When used on a narrow street, advance turn lanes can produce a cluttered look, as shown in Figure 13. However, advance lanes do serve to move switches out of the intersection, thus reducing the impact of concentrated special work.

Generally, an advance turn lane should be used for all left turns when there are two or more lanes of moving traffic in the direction of the turn approach. An exception may occur when the turn is not regularly used. In some locations, an advance left turn can be designed with a gradual shift in the wire from the normal position to the left turn position. This will both reduce visual impact and often improve operations. Advance right turn lanes are appropriate only when there are two or more lanes of moving traffic and when high levels of pedestrian movement commonly delay right turn movements.

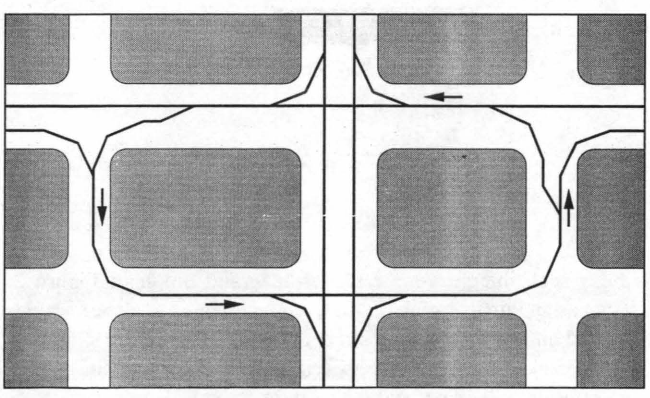

FIGURE 11 Use of one-way wire to provide all possible turns without complex intersections.

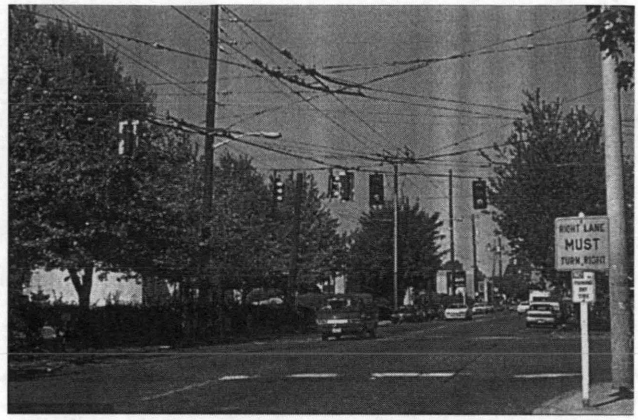

FIGURE 12 Diverging route on narrow street; 15th Ave. E and E. Thomas St., Seattle. Compare this figure with Figure 3 to observe effect of street width on appearance.

FIGURE 13 Advance turn lane on narrow street; Divisadero and Jackson Sts., San Francisco. Note that advance turn lane can be used only by moving into opposite direction through lane.

Trailing turn lanes, as well as long advance lanes, can be used to allow turning vehicles to bypass bus stops. This design feature is usually found in downtown areas where different route groups have separate stops on the same street. Trailing turn lanes offer no other operational advantage and are not recommended except for this purpose.

Finally, although garage OCS design is not part of this paper, it should be noted that garage OCS sometimes overflows into an adjacent street. The use of street access to individual garage tracks should be avoided if at all possible, as the concentration of special work and poles will be much greater than in any other design situation.

This paper is a modification and expansion of one section of the Overhead Contact Systems Visual Impact Handbook, prepared by Urbitran Associates, Arthur Schwartz Associates, and Skidmore, Owings and Merrill under TCRP contract D-4.

Publication of this paper sponsored by Committee on Rail Transit Systems.

Electric and Magnetic Fields and Electric Transit Systems

ROBERT B. FISHER

Over the past decade there has been increased public concern about possible health effects resulting from exposure to low-frequency electric and magnetic fields (EMF). Although the main attention has focused on utility companies' high-voltage transmission lines, this public concern over EMF is likely to have an adverse effect on the installation or expansion of electrified railroad, transit, or trolley bus systems. It is yet another reason for public opposition to new electric rail systems or system expansions. Concerns may come from a variety of areas, including people living or working adjacent to electrified transit routes, riders, operators, and maintenance personnel. In addition, railroad and transit systems frequently share rights-of-way (ROW) with public utility high-voltage transmission lines, often with the utility and transit company jointly occupying the same support structures. This greatly benefits both parties, especially in urban areas, where it is expensive and difficult to obtain the necessary ROW. However, this often results in transit passenger stations being located beneath or in relatively close proximity to the utility company's high-voltage transmission lines. Some of the more prominent developments in EMF research are reviewed and how the issues pertain to electric transit operations is discussed. It identifies the areas where long-term exposure to low-frequency EMF has been linked to health hazards, the reliability and controversy of these findings, and how these relate to AC and DC traction operations in terms of both real and perceived risks. Ways of reducing AC field strengths are reviewed, along with suggestions on how transit agencies can alleviate the concerns. Current research efforts, legislative efforts in the United States and worldwide, and state and federal standards are also discussed.

Any electrical conductor or apparatus is a source of electric and magnetic fields (EMF). Electric fields are a function of the electrical potential of the conductor and are expressed in terms of volts per meter (V/m).

The electric current flowing through the conductor creates a magnetic field. The strength of the magnetic field, also called the magnetic flux density, is measured in terms of lines of magnetic flux passing through an area at right angles to the flux. The unit of measurement of magnetic fields is gauss (G).

EMF can be either static (a result of DC voltage and current) or time-varying (a result of AC voltage and current). The earth's static magnetic field has a strength of about 1 G.

Concerns have been raised about the safety of long-term exposure to low-frequency EMF. Low frequency generally refers to the 3- to 3,000-Hz range. However, the most attention has focused on the commercial frequencies of 60 Hz (United States) and 50 Hz (Europe). In addition, certain industries (including electrified railroads) have traditionally used lower frequencies, i.e., 25 Hz (United States) and 16-2/3 Hz (Europe).

Frankford Elevated Reconstruction Project, Southeastern Pennsylvania Transportation Authority, 500 Bustleton Avenue, Philadelphia, Pa. 19149-3404.

Research indicates that if a health problem exists, it is a result of the magnetic fields rather than the electric fields. Therefore, this paper will focus primarily on the magnetic fields. Most of the research has pertained to the fields emitted by high-voltage transmission lines. A 1992 report issued by the Environmental Protection Agency (EPA) (*1*) provided typical field strengths emitted by various power lines in milligauss (mG) (see Table 1).

Because all electrical apparatus emits some level of EMF, a room is considered "clean" or free of low-frequency EMF if the level is less than 1 mG.

The issue of whether exposure to low-frequency EMF poses a health threat was first raised in 1979 when epidemiological studies by Wertheimer and Leeper (*2*) claimed there was a higher incidence of leukemia occurring in children living adjacent to overhead power lines. Since that time, a number of other epidemiological studies have also indicated that long-term exposure to low-frequency EMF (particularly in the 50- and 60-Hz range), both residential and occupational, increases the risks of certain cancers by as much as 2.5 to 3 times. These studies have been based on the configuration of overhead wires in the vicinity of residences, or on job descriptions, and have been based on calculated field strengths. However, these results have not been confirmed by studies that measure field strengths. In addition, biological studies have failed to provide any explanations to support this apparent effect, and other epidemiological studies have produced negative results.

Some experts contend that the low numbers of cases involved make the results questionable, implying that one or two cases would significantly alter the statistics. Also, it has been claimed that the studies may be influenced by confounding factors (herbicides or some other element associated with transmission lines rather than magnetic fields). Household appliances such as electric hairdryers, shavers, blankets, etc., and types of household wiring where the neutral wire is run separately from the line wire have also been cited as potential hazardous sources of magnetic fields. However, none of the studies to date have linked short-term exposure to magnetic fields with health hazards. Therefore, with the exception of appliances or wiring that would result in long-term exposure to magnetic fields, it is unlikely that these would pose a health threat.

The facts become very clouded by the emotional and legal issues surrounding the topic. Public attitude toward risk is greatly influenced by: (a) fear of the unknown and the unseen; (b) lack of control; (c) distrust of technology; and (d) potential harm to children.

All of these conditions apply to magnetic fields. In addition, high-voltage transmission lines and substation facilities are not welcome additions to residential communities and would almost certainly be strongly opposed regardless of the EMF issue, not to mention that this issue has already adversely affected property values, unquestionably the largest single investment that most people make in their lifetime.

TABLE 1 Transmission Line Typical Magnetic Field Strengths

		Magnetic Field (mG)				
		Distance From Line				
Voltage Level	Usage	Max. Row	15.25m (50 ft.)	30.5m (100 ft.)	61m (200 ft.)	91.5m (300 ft.)
115 kV	Average	30	7	2	0.4	0.2
	Peak	63	14	4	0.9	0.4
230 kV	Average	58	20	7	1.8	0.8
	Peak	118	40	15	3.6	1.6
500 kV	Average	87	29	13	3.2	1.4
	Peak	183	62	27	6.7	3.0

Information courtesy of Bonneville Power Administration

IMPACT ON UTILITY PROJECTS

Numerous cases have been cited in recent years in which public concerns over EMF have resulted in the delay or replanning of electric transmission lines and substations. Utility companies have considered and, in some instances implemented, various alternatives to reduce magnetic fields. These include: (a) wider ROW; (b) construction techniques, such as installation of additional static wires and split-phase construction (an example of how conductors can be rearranged to reduce field strengths on both single- and double-circuit lines is shown in Figure 1); and (c) replacing the transmission line with underground cables.

However, these techniques invariably result in significant increases in construction and maintenance costs, and in the case of split-phase construction, the potential for operational difficulties. One approach to this problem is to adopt what is known as the ALARA principle. This translates to reducing field levels "As Low as Reasonably Achievable." A guideline developed in Sweden is that field levels should not exceed 10 times normal if costs are not excessive. Some individuals have expressed concern with this approach because, to some extent, it reinforces concern by the public and workers that there must be some risk. However, in many instances it has been necessary to make some concessions just to keep vital transmission line, or substation projects on schedule. In addition, with the level of ongoing research, it would seem prudent to reduce fields if the costs are negligible. It also demonstrates that the industry is acting responsibly, thereby possibly increasing the "trust factor." In recent years, many projects have been delayed or even abandoned because of public opposition, with concerns over EMF health effects as the prime reason. In some instances, utility companies have changed routes and substation locations and even opted to install underground cables.

The following are some of the more recent incidents involving EMF. In November 1993, it was reported in the construction industry biweekly trade magazine *ENR* that a cogeneration project in Washington, D.C., had been put on hold until "more is known about the health effects of electrical and magnetic fields from reactivated power lines."

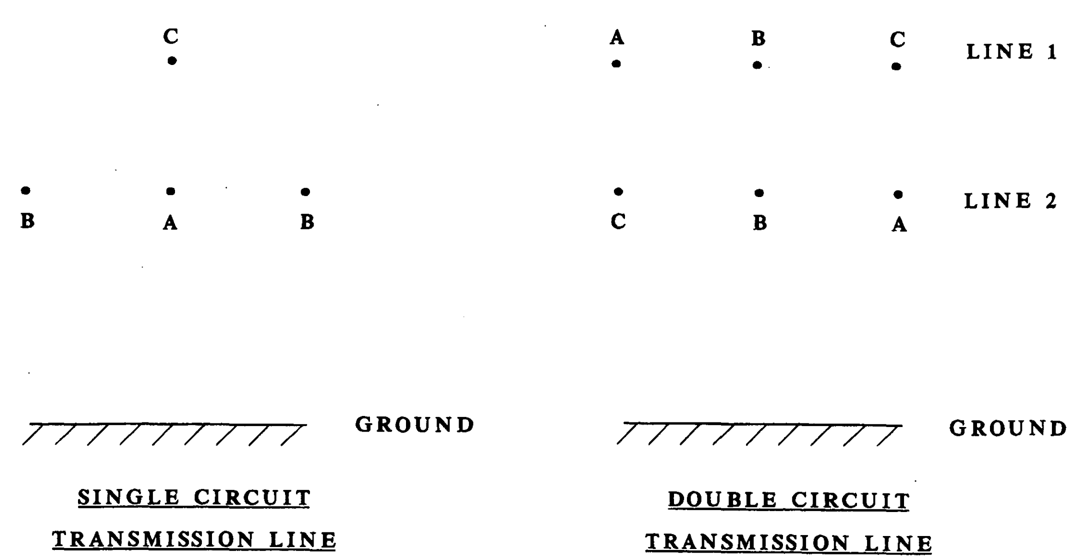

FIGURE 1 Examples of split-phase construction.

In another instance the energization of a 230-kV power line north of Philadelphia, Pa, was delayed 18 months because of protests about EMF issues. This was a former 132-kV, 25-Hz, single-phase line on Conrail's railroad ROW that had been reconductored and upgraded to a 230-kV, 60-Hz, three-phase line. Magnetic field strengths at the edge of the ROW were calculated not to exceed 26 mG under normal operating conditions (i.e., 90 percent of the time). In the final ruling on this case, the Administrative Law Judge concluded that there was no "conclusive causal connection between exposure to EMF and adverse human health effects because of the inconclusive nature of said research and studies." However, the ruling did require that should adverse health effects be scientifically established in the future, the utility company may be required to make changes to the line.

As recently as August 1994, the Clifton City Council and Education Board in New Jersey voted in favor of paying Public Service Electric and Gas Company (PSE&G) $35,000 to reconfigure a transmission line adjacent to one of the city schools. The State Regulatory Board had earlier required utility companies to measure magnetic field levels at all primary and secondary schools located near any transmission lines of 69 kV and above. Average readings between 14 and 22 mG had been recorded at the school in Clifton, which was the second highest reading in the state. In this case, PSE&G had refused to pay for the reversal of conductors, which it is calculated will reduce the EMF levels by 58 percent. The city will attempt to recover the money if it is later proven that these magnetic field levels pose health threats.

ELECTRIC TRANSIT SYSTEMS

Public concerns over EMF can affect electric transit systems in a variety of ways. First, utility companies and electric transit systems often share ROW, and passenger stations are located near the high-voltage transmission lines. Second, in the case of AC railroad electrification, the overhead catenary distribution system also is a source of low-frequency EMF. Also, AC electrification systems require high-voltage feeds from the utility companies, often at the 230-kV level to keep harmonic distortion and phase unbalance within utility-company limits. This may also require the construction of high-voltage transmission lines and obviously requires high-voltage substations.

DC systems also require power supply substations, although these are at a much lower voltage than the AC railroads. However, there is often no choice other than to locate these in residential areas. In the case of light rail and trolley bus systems, overhead power distribution systems are also required. However, these are low-voltage DC systems.

In addition, all electric transit vehicles contain electric traction motors that can generate relatively high magnetic fields.

It is clear then that all types of electric transit systems will result in some exposure to EMF for passengers, company employees, and people living adjacent to the transit lines.

AC ELECTRIFICATION

Problems with magnetic fields on AC-electrified railroads occurred long before the current EMF debate started. The high fields developed by the single-phase feed (the catenary) with rail and ground return result in high-induced voltage in any wayside conductors, or any other conducting material (*i.e.*, fences) that run parallel to and in close proximity to the track for any significant distance. This can result in interference in signal and communication circuits, and also results in unsafe induced voltages. Under normal conditions the induced voltage should be kept under 50 V, although higher voltages can be tolerated under fault conditions.

Descriptions of the two types of systems developed to mitigate interference and induced voltages follow

Booster Transformer System

With this system, a conventional center fed system has a return conductor with booster transformers added to its return circuit. The booster transformers are 1:1 current transformers with the primary windings connected in series to the catenary and the secondary windings in series with the return conductor (see Figure 2). The

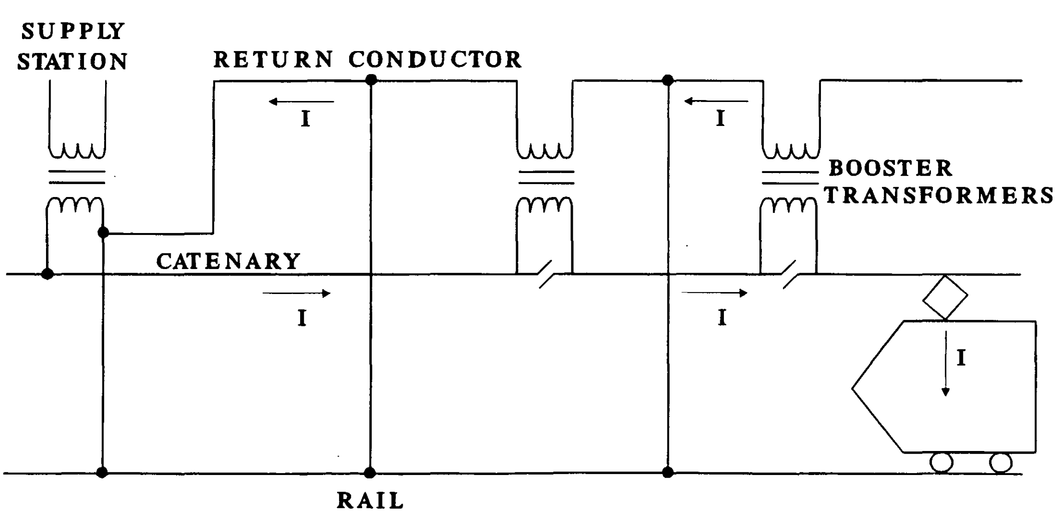

FIGURE 2 Booster transformer system.

return conductor is insulated from the catenary poles and is connected to the rails midpoint between booster transformers.

Because the booster transformers have opposing windings, the return current is forced into the return conductor. The return conductor is located between the catenary and the circuits to be protected, which effectively shields these circuits from interference. Booster transformers are placed approximately 1.6 km (1 mi.) apart for effective interference suppression. This coincides with the overlaps on auto tension catenary systems, which can be insulated to provide the section breaks for the booster transformer primary connections.

The disadvantages of the booster transformer system are (*a*) the capital cost, which includes the cost of the booster transformers; (*b*) the return conductor, which has to be sized to carry the same current as the entire catenary; and (*c*) possibly heavier poles and foundations to carry this heavy conductor. In addition, the impedance of the catenary and return circuit is increased by up to 30 percent, with a corresponding reduction in substation spacing by up to 30 percent.

The advantage is that booster transformers can be added only in sections where interference suppression is required. Although used extensively in Europe, the booster transformer system has not been used in the United States. Incidentally, a return conductor without the booster transformers can also be used to provide some shielding.

Autotransformer System

The configuration of the autotransformer system is shown in Figure 3. In this system, the power is supplied through the feeder and the catenary, and stepped down to the catenary to rail potential at the auto transformers. Once a train has passed an autotransformer location, the catenary current and feeder current are equal. As they are in opposite directions, the same mitigation is provided as with booster transformers.

The main advantage of the autotransformer system is that the bulk of the traction power is essentially transmitted at the catenary-to-feeder voltage. In modern systems, the feeder and catenary voltage are the same, *i.e.*, on Amtrak's New Haven-to-Boston line, both will be 25 kV. Earlier systems, such as SEPTA's former Reading Railroad, had a 22-kV feeder and an 11-kV catenary. This system was built in 1933 and is still in operation today.

The disadvantage of the auto transformer system is that the auto transformers are located further apart, usually about 8 km (5 mi). As the mitigation is not fully effective when trains are located between auto transformer stations (the same applies to booster transformer systems), there are longer periods when the interference mitigation is not fully effective.

The autotransformer system was originally developed to extend the railroad electrification systems into rural areas where power supply points were not available. This system is now attractive to minimize the number of supply substations because of the environmental problems encountered in building substations and high-voltage feeder lines.

DC TRANSIT SYSTEMS

Because the DC transit systems primarily generate static EMF, the same problems encountered with AC electrification systems do not exist. However, with the higher harmonic content of some of the

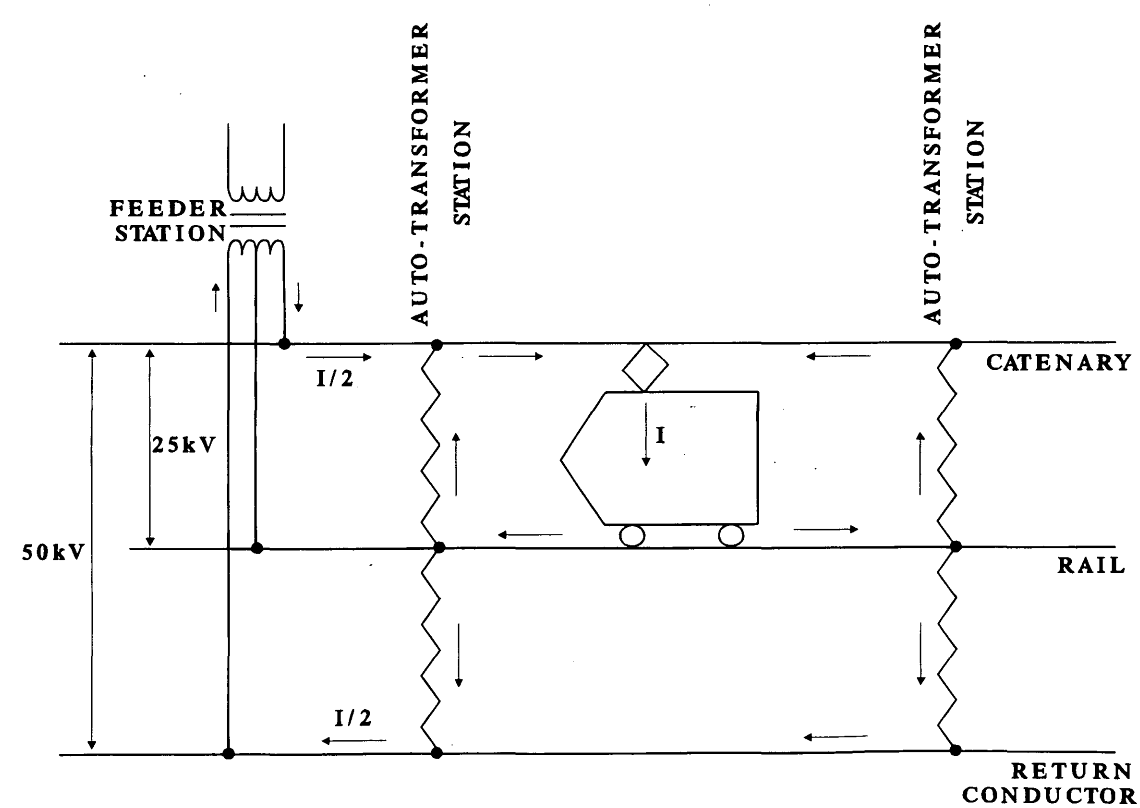

FIGURE 3 Autotransformer system.

newer traction motor systems, especially AC motors, some low-frequency magnetic fields are generated. However, it is extremely unlikely that these would result in any significant low-frequency fields being emitted from the traction distribution system. Nevertheless, these systems tend to be located closer to residences; therefore, EMF concerns raised by people living nearby should be expected.

Trolley coach systems have the added advantage that the positive and negative lines are located very close together, usually about 61 cm (24 in.) apart. This further eliminates the possibility of magnetic fields of any significance existing except very close to the overhead wires. In addition, the currents on these systems are generally far lower than other systems.

EMF RESEARCH EFFORTS

As stated previously, the concerns were raised in 1979 as a result of epidemiological studies conducted by Wertheimer and Leeper (*2*). A field study of homes in the greater Denver area was conducted in 1976–1977 that noted an excess of wiring configurations near homes where children had developed cancer. This study suggested that children in homes adjacent to overhead power lines had 2 to 3 times the risk of dying from certain types of cancer compared to other children. Although this study was heavily criticized, especially in terms of whether wire configuration could be accurately related to EMF, it did cause a lot of concern and spurred additional research.

In 1992 a report was issued by Feychting and Ahlbom (*3*) from the Karolinska Institute, Stockholm, Sweden, that again cited increased risk of childhood cancer in homes located near high-voltage transmission lines. This was considered a well-respected study. It not only analyzed wire configuration, but calculated field strengths based on utility company load records. Although this study again indicates an increased risk, the low number of cases involved may be insufficient to support this conclusion.

At the same time, various occupational studies (*4*) have been performed comparing job descriptions with incidents of cancer. Although the results of many of these studies indicate that individuals with electrical-type job descriptions have a higher incidence of certain cancers, it cannot be concluded that this is a result of EMF exposure or if it is the result of other hazards that electrical workers encounter in the workplace.

Laboratory studies have so far failed to provide any consistent findings to support concerns over EMF. It is generally agreed that if there is a link between EMF and cancer, it would be in terms of promoting rather than initiating the onset of the disease.

Although most of the research has focused on the utility industry, some research has been conducted in the transportation field. This has been mainly spurred by the increased interest in maglev and high-speed rail systems. Much work has been done as part of the Environmental Impact Statement for the New Haven-to-Boston Electrification Project, including measuring field levels on various railroad and transit operations.

TRANSIT EMF LEVELS

Prompted by the need to initiate high-speed electrification and maglev projects, the Federal Railroad Administration of USDOT sponsored research (*5*) into the EMF generated by various modes of electric transportation systems including maglev, 60-Hz and 25-Hz electric rail, 750-V DC (3rd rail) mass transit, and 600-V light rail transit (LRT) and trolley coach operations. This research has focused on measuring the EMF levels that passengers, transit workers, and people living adjacent to transit operations would be exposed to.

Not surprisingly, at most wayside locations the magnetic field levels were very intermittent, high when a train was in that feed section, and then rapidly falling off. Also, although the magnetic fields were sometimes relatively high adjacent to the tracks, these rapidly fell off as you moved away from the tracks. For example, a field strength of 100 mG, 9 m (30 ft) from the track fell to 10 mG, 30 m (100 ft) from the track, and at 92 m (300 ft) was less than 1 mG.

The magnetic field levels measured in the passenger compartments of various transit vehicles are given in Table 2, and on the platform area in Table 3, for a cross section of electric rail and transit systems. It should be noted however, that some of the higher fields, i.e., in the WMATA 3000 cars, occur close to the floor and fall off rapidly in the first 60 cm (2 ft).

TABLE 2 Magnetic Fields in Passenger Compartments on Trains

	Magnetic Field (mG)			
	Static		5-2560 Hz	
System	Maximum	Average	Maximum	Average
NEC(a) 11 kV, 25 Hz	1,763	606	782	133.8
NEC 11 kV, 60 H	1,039	630	408.4	52.5
NEC Non-electrified	1,033	569	26.5	5.2
WMATA(b) -Cam Cars (750 V dc)	4,714	1,103	64.8	9.4
WMATA-3000 Cars (750 V dc)	23,732	2,685	443.6	177.8
MBTA(c)-LRT (600 V dc)	1,981	534	68.4	5.7
MBTA-Trolley (600 V dc)	3,074	719	26.0	4.5
MBTA-Trolley Bus (600 V dc)	467	273	13.2	3.2

(a) Amtrak's Northeast Corridor
(b) Washington Metropolitan Area Transit Authority
(c) Massachusetts Bay Transportation Authority

TABLE 3 Magnetic Fields on Station Platforms

	Magnetic Field (mG)			
	Static		5-2560 Hz	
System	Maximum	Average	Maximum	Average
NEC(a)-11 kV, 25 Hz	970	422	550.8	39.6
NEC(a)-11 kV, 60 Hz	1629	650	417.6	62.2
NJT(b)-11 kV, 60 Hz	615	525	213.2	28.8
WMATA(c)-750 V dc	2065	455	66.6	3.1
MBTA(d)-600 V dc catenary	1718	612	82.0	8.6

(a) Amtrak's Northeast Corridor
(b) New Jersey Transit
(c) Washington Metropolitan Area Transit Authority
(d) Massachusetts Bay Transportation Authority

REGULATIONS AND STANDARDS

Currently no regulations exist in the United States governing the allowable levels of EMF. Both Florida and New York have established standards for the maximum EMF levels for transmission lines. However, it is interesting that neither of these standards is health related.

Florida's standards for 230-kV or smaller lines are:

1. Electric field	8 kV/m	maximum
	2 kV/m	edge of ROW
2. Magnetic field	150 mG	(max load) edge of ROW

New York's standards are:

1. Electric field	11.8 kV/m	maximum
	1.6 kV/m	edge of ROW
2. Magnetic field	200 mG	(max load) edge of ROW

The World Health Organization recommends limiting long-term exposure to electric fields between 1 and 10 kV/m. Its recommendations for magnetic fields are 20,000 G for static (DC) fields and (by proportion) 10 G at power frequency levels.

The International Radiation and Protection Association (IRPA) established maximum limits of 1 G (24-hour exposure) to 10 G for a few hours per day.

The National Radiological Protection Board NRPB (UK) (*6*) has established similar standards. However, this document also references the Swedish and Danish (*7*) epidemiological studies and concludes that these were "well controlled and substantially better than those that previously reported association with childhood cancer." However, the document goes on to state that the studies report few cases, and do not establish that exposure to EMF is a cause of cancer. It does acknowledge that the studies provide "weak" evidence that the possibility exists, but contends the risk, if any, would be very small.

The EMF issue has also been of concern to the electrical engineering professional societies. The Institution of Electrical Engineers in the United Kingdom (IEE) established a Health and Safety Committee in 1992. In May 1994 the IEE issued a preliminary view "that there is nothing in the currently available evidence to prove the existence of the effects claimed. If any such effects do exist, then their incidence within the population, taken as a whole, must be very small." The IEEE in the United States has issued similar position statements.

As stated, no federal regulations have been established. However, government involvement has recently increased. H.R. 1665: The Electromagnetic Labeling Act of 1993 was recently introduced in Congress. This bill would have required products with field strengths greater than 100 mV/m and 1 G when measured 2.5 cm (1 in.) from the product to be labeled with simple information on the EMF emitted from that product. So far this bill hasn't made much headway because current research has not established a clear link between EMF and health effects.

However, Section 2118, Electric and Magnetic Fields Research and Information Dissemination Program of the U.S. Energy Policy Act of 1992, authorized the appropriation of $65 million for research efforts from Fiscal Years 1993 through 1997. The purpose of this program is to:

1. Determine whether exposure to electric and magnetic fields produced by the generation, transmission, and use of electric energy affects human health;
2. Conduct research, development, and demonstrations with respect to technologies to mitigate any adverse human health effects; and
3. Disseminate information to the public.

OTHER SOURCES OF EMF

Of course there are many other sources of magnetic fields both in the house and in the work place. The EPA document issued in 1992 lists various appliances with the lowest, medium, and highest levels of magnetic fields measured at various distances from the item. A few of the higher ranked household appliances are listed in Table 4 (higher values only).

Conventional electric blankets have peak values of nearly 40 mG, 5 cm (2 in.) from the surface, although newer-model positive temperature coefficient (PTC) low-magnetic-field blankets have fields less than 3 mG, 5 cm from the surface.

Therefore, while many appliances can generate high fields close by, they generally fall off rapidly.

TABLE 4 Household Appliances

	Magnetic Field (mG)			
	Distance			
Appliance	15 cm (6 in.)	30 cm (12 in.)	61 cm (24 in.)	122 cm (48 in.)
Hairdryer	700	70	10	1
Electric Shaver	600	100	10	1
Can Openers	1500	300	30	4
Microwave Oven	300	200	30	20
Mixers	600	100	10	-
Vacuum Cleaners	700	200	50	10
Color TV	-	20	8	4

- Data not available

OTHER FACTORS

Aside from the inconclusive results of the scientific research to date, many other issues cloud the debate on the seriousness of the EMF health issue.

Various media articles have sensationalized the topic, sometimes making it difficult to separate fact from fiction. Probably the most famous are the articles in the *New Yorker* by Paul Brodeur, followed by his books, *The Currents of Death* and *The Great Power Line Cover-up*. In addition, the issue has been covered in movies, a variety of news magazines, and numerous newspaper articles.

A variety of legal actions have stemmed from the EMF issue, many settled out of court. As a result of the potential for litigation, many utility companies have been reluctant to openly discuss the issue.

In addition, the general distrust of the public toward industry is a major factor. Chernobyl and Three Mile Island in the nuclear industry, and Love Canal and numerous other incidents regarding hazardous materials tend to make people fear the worst, even when the scientific evidence regarding EMF is relatively weak.

Of course another major problem is the "Not In My Back Yard" (NIMBY) syndrome. High-tension power line projects were being strongly opposed for aesthetic reasons long before the EMF debate. Similarly, high-speed rail, especially electrified, and most electric transit projects usually face strong opposition from adjacent property owners.

As a result of the EMF concerns, property values have generally declined in residential areas adjacent to high-voltage transmission lines and substations.

Finally, because of the uncertainty on how, if at all, EMF is a health hazard, it's difficult to equate the risk associated with EMF with other risks encountered in everyday life. It's interesting that many people voluntarily expose themselves to risks much greater than EMF, such as smoking. Even the concerns over radon gas seem to have declined in recent years.

CONCLUSION

It is unlikely the question concerning exposure to relatively low levels of low-frequency EMF as a health threat will be conclusively answered in the near future, if ever. Therefore, the railroad and transit industry must be prepared to address the concerns of riders, workers, and people living adjacent to electrified transit operations.

From the research and measurements taken to date, it can be concluded that although maximum wayside values of magnetic fields are relatively high on AC railroads compared to utility lines, these are of short duration. In addition, riders would only be exposed to these fields for a relatively short period of time. Not surprisingly, DC systems exhibit much lower magnetic field values.

Similarly, low-frequency magnetic fields on board the vehicles are much higher for AC electric railroads than for DC systems, with the fields on the electric trolley bus being the lowest. However, it is noted that a relatively high AC field was recorded on the WMATA 3000 cars. Therefore, even DC traction systems must be considered a potential source of low-frequency EMF, especially those with modern traction drive systems.

Public concern over the safety of EMF continues to plague the utility industry, attracting a lot of media attention. Early in 1994, an EMF-monitoring device was advertised in a mail order brochure of "home safety gadgets." This monitor was calibrated from 1 to 24 mG, with three zones, from green (safe) to red (potentially unsafe), and sold for $99.95. With this in mind, it could be hard to convince the public that fields of 1,000 mG are safe. Therefore, to avoid enabling the EMF issue to become a deterrent to new transit system starts, it is important that research continue in this area and that the results are disseminated throughout the industry.

REFERENCES

1. *EMF In Your Environment; Magnetic Field Measurements Of Everyday Electric Devices.* Environmental Protection Agency. 402-H-92-008 Dec. 1992.
2. Wertheimer, N. and E. Leeper. Electrical Wiring Configurations and Childhood Cancer. *American Journal of Epidemiology*, 1979, pp. 273–284.
3. Feychting, M. and A. Ahlbom. *Magnetic Fields and Cancer in People Residing Near Swedish High Voltage Power Lines.* IMM-rapport 6/92, Karolinska Institute, Stockholm, Sweden, 1992.

4. Savitz, D. A. *Overview of Epidemiologic Research on Electric and Magnetic Fields and Cancer.* American Industrial Hygiene Association, 1993, pp. 197–204.
5. Electric Research and Management, Inc., *Safety of High Speed Guided Ground Transportation Systems: Comparison of Magnetic and Electric Fields of Conventional and Advanced Electrified Transportation Systems.* U.S. Department of Transportation, Federal Railroad Administration (USDOT/FRA). Report No. DOT/FRA/ORD-93/07, Aug. 1993.
6. *Board Statement on Restrictions on Human Exposure to Static and Time Varying Electromagnetic Fields and Radiation.* National Radiological Protection Board, United Kingdom, 1993.
7. Olsen, J. H., A. Nielsen, and G. Schulgen. Residence Near High-Voltage Facilities and Risk of Cancer in Children *British Medical Journal,* 367.891, 1993.

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PART 2

Rail, Intermodal, and Light Rail

Diverting Automobile Users to Transit: Early Lessons from the Chicago Transit Authority's Orange Line

SARAH J. LABELLE AND DARWIN G. STUART

After only 12 months of operation, the Chicago Transit Authority's new Orange Line, providing rapid rail service from Chicago's Loop to Midway Airport, had reached a weekday ridership of 37,500 passengers. Preliminary analysis indicated that the line had increased transit ridership overall in the southwest corridor by 31.0 percent, raising transit's mode share of work trips from 16.4 percent to 21.5 percent. Based on an on-board rider survey done after 4 months, nearly one-quarter of daily boardings were new to transit, representing former automobile commuters or new trips for which the automobile was a candidate. That share grew to over 25 percent by the end of the first year. Core, secondary, and tertiary markets were defined in March 1994 in the southwest corridor, together providing 84 percent of the line's ridership. Demographic and travel characteristics of the transit riders surveyed are compared with comparable market-area data from the 1990 U.S. Census. Survey data regarding the intensive marketing campaign that accompanied the line's opening are analyzed. A separate analysis comparing diverted and new transit riders with those who shifted from other transit services is given. A series of guidelines is drawn for successfully inaugurating major transit-service improvements designed to decrease reliance on automobiles. The origin-destination and access-mode data from the March survey were also used to measure the net decrease in automotive cold starts and vehicle kilometers traveled. These measures were developed to estimate the air-quality benefits of this new rapid-rail service.

The Chicago Transit Authority's (CTA's) new Orange Line is the first entirely new rapid transit line in Chicago and its suburbs since 1969, when the Dan Ryan Expressway median line opened, and it is the first rapid rail in the southwest corridor, which connects the Loop to Midway Airport. The Orange Line opened for service on October 31, 1993. Proponents, who fought long and hard for southwest side rail transit, said people would come out of their cars to use good, fast transit.

The environmental impact statement, completed in 1982, counted on those automobile diversions for the anticipated environmental benefits (*1*). It was projected then that one-quarter of the riders would come from cars, generating less tailpipe emissions, thereby lessening Chicago's ozone and carbon monoxide problems.

The purpose of this study was to determine whether these expectations have been realized. It also presents a profile of the riders at this early stage in what will be long years of rapid-rail service in the southwest side.

The Orange Line runs around the Chicago Loop, connecting with the Brown, Red, Blue, and Purple line trains, and the soon-to-be reborn Green Line. It travels 18.8 km (11.75 mi) to Midway Airport following freight rail rights-of-way, close to the population centers of the southwest side. The line was built by the city of Chicago, as a new rail start funded in part by the U.S. Department of Transportation (DOT). It was completed within budget and on schedule.

The map in Figure 1 presents the market area of Orange Line riders, as determined from a March 1994 survey of home zip codes (*2*). The boundaries shown indicate the home location of 84 percent of weekday riders in an area extending from Dearborn Park on the northeast through the southwest-side neighborhoods as far as Hickory Hills. Other suburbs in the market area include Burbank, Bedford Park, Bridgeview, Hometown, Justice, Merrionette Park, Oak Lawn, and Summit. Two subareas are also shown, depicting the home location of 51 percent and 17 percent of Orange Line riders. Remaining trip origins are drawn from across the entire CTA service area, such as commuting-to-work trip (the "work trip") destinations lying within the corridor or to the airport for air travel. Of all Orange Line riders, 84 percent resided in Chicago (north and south sides), 13 percent were suburban residents (12 percent south and 1 percent north), and 3 percent were from outside the region.

CTA received a 2-year $1 million grant from the federal Congestion Mitigation and Air Quality (CMAQ) program to market the new Orange Line, which serves 16 stops from the Loop to Midway Airport. Adequate marketing was deemed essential to attract projected new riders to transit and to realize the promise of reduced air-pollutant emissions. The CTA budget did not allow significant marketing expenditures; hence the grant was sought.

CORRIDOR DEMOGRAPHIC AND WORK TRAVEL CHARACTERISTICS: 1990 U.S. CENSUS

To provide an understanding of the overall travel market in the southwest corridor, basic demographic and work travel characteristics from the 1990 U.S. Census were compiled. These data were sorted by the three markets shown in Figure 1, as revealed by the March 1994 transit rider survey. These commuter-travel markets were termed core, secondary, and tertiary markets, and are oriented primarily toward the work trip.

The southwest corridor can be characterized as middle class, with median household income at $24,900; there is a fairly even distribution of incomes across lower and middle income ranges. Household size averages 3.0, higher than the average for either Cook County or the city of Chicago as a whole, for which the average is 2.7. Automobile ownership is relatively high. One-half of corridor residents are white, with a significant portion having Eastern European heritage; nearly one-quarter are Hispanic, and one-quarter are African-American.

Market Research Department, Chicago Transit Authority, P.O. Box 3555, Chicago, Ill. 60654.

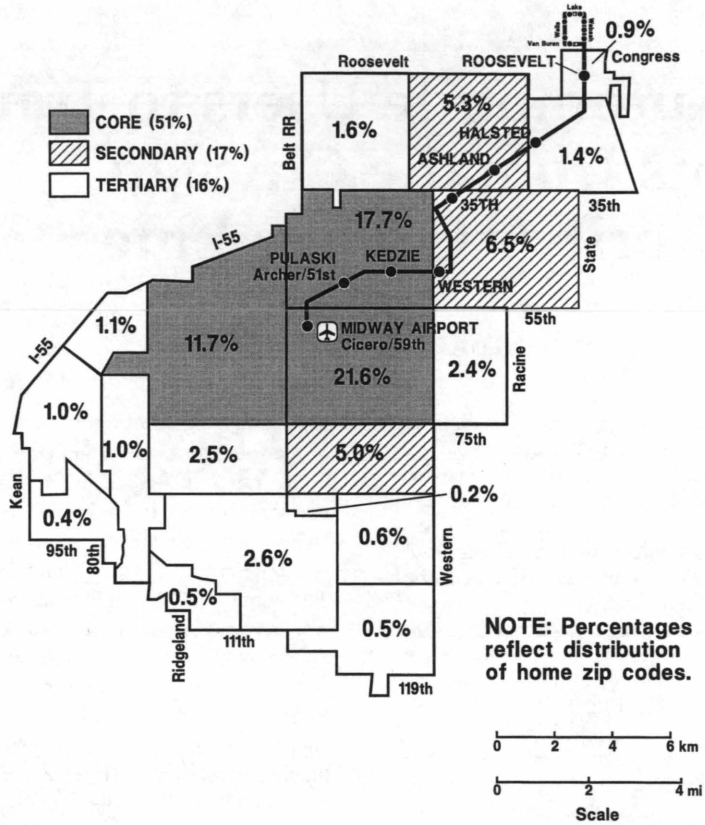

FIGURE 1 Orange Line market area: March 1994 home zip codes of 84 percent of weekday riders (2).

Driving alone was the primary work-trip mode in 1990, followed by carpooling (16.8 percent) and a relatively large (14.6 percent) usage of CTA buses. About 75 percent of this bus travel was via express routes along the Stevenson Expressway into the Chicago Loop. Among the three commuter markets, the level of bus and carpool use was highest in the secondary market and lowest in the tertiary market. This comparison indicates that there was higher availability of and reliance on the automobile in the tertiary market, and that transit access (before the existence of the Orange Line) was better for the secondary market (also indicated by the 3.6 percent use of other rapid transit lines).

Multiworker households form a significant component of the work force in the southwest corridor, with 53 percent of households containing two or more workers. This factor may influence both the pre-Orange Line level of transit use, as well as the level of additional transit ridership attracted by the Orange Line after its opening. Work-trip travel times in 1990 averaged 33.6 min in the corridor. There is relatively little difference among the three commuter markets.

TRANSIT RIDER DEMOGRAPHICS AND TRAVEL CHARACTERISTICS: 1994 SURVEY

The March 1994 survey of riders on CTA's Orange Line, although undertaken only 4 months after the opening of the line, gives a useful profile of the travel and demographic characteristics of new southwest side CTA rail passengers (*3*). An important feature of the survey was to learn more about those riders who formerly traveled by automobile, to allow measurement of the line's air-quality benefits. No standard methods are in place from either the U.S. DOT or the Environmental Protection Agency on how to assess fairly the air-quality benefits of a new rail line.

Survey Design

Although origin-destination (O-D) information was desired primarily for current and former automobile users and those making new trips, all riders were asked trip purpose, names of the street intersection and city of their trip's origin and destination, and mode of access to the Orange Line. For the air-quality analysis, only the new rider O-D information was used in the analysis of trip length.

The survey also asked riders how they made the trip before the Orange Line opened, and where they had seen or heard about the line. Riders were also asked for standard demographic information, including sex, zip code at home, ethnicity, age, household size, household vehicle availability, and income. Suggestions for improvements to the line and respondent contact information were also requested.

On the basis of this survey of initial riders, the market area was larger than planners envisioned in 1982, and larger than was estimated from a more recent analysis of market potentials (*4*). There were patterns within the area: core riders (51 percent) came from three zip codes (60629, 60632, and 60638) that encompassed the Kedzie, Pulaski, and Midway stations and the area west and south of Midway Airport beyond the rail line (see Figure 1). To cover

two-thirds (67.8 percent) of the home locations, three additional zip code areas (60608, 60609, and 60652)—the "secondary" market—must be added, covering the Western, 35th, and Ashland stations and a neighborhood further south of those three core zip codes. The last one-third of the riders were spread out over a large area, and included out-of-town riders using Midway Airport.

Survey results are presented here in two ways. First, basic trip characteristics and demographic characteristics of all survey respondents are described. This includes trip purpose, mode of access, geographic distribution of riders, prior mode used, automobile ownership, household income, and related characteristics. Second, many of these characteristics for new riders—not previous CTA bus or rail passengers—are given, including trip length.

Demographic Characteristics

Fifty-four percent of survey respondents were female. The age distribution of riders was primarily among the working-age population, with 53 percent of all riders aged 18 to 34. Ethnicity and race generally reflected overall corridor characteristics: 61 percent of respondents were white, 22 percent Hispanic, and 13 percent African-American.

Just over one-third (36 percent) of respondents were from one- or two-person households, although another 40 percent were from three- or four-person households. The mean household size was 3.4 persons. Household incomes were fairly evenly distributed across a range of $10,000 increments, with 9 percent under $10,000 and 16 percent over $60,000. The income levels of survey respondents were generally higher than the 1989 incomes reported in the 1990 Census, which is partly explained by inflation. Only 15 percent of households reported having no automobiles available, with 37 percent having one car and 33 percent having two cars. Automobile ownership of CTA-rider households was significantly higher than that reported for the market area in the 1990 Census, in which households with no automobile were measured at 25 percent.

Travel Characteristics

Trip Purpose

Trips made on the Orange Line were most likely for work (60.6 percent) or school (13.6 percent); 3.4 percent were strictly for airline travel (see Table 1). Another 6.4 percent were work-related trips. Only 2.2 percent were shopping trips, and 5.0 percent were social. Work was more dominant as a trip purpose for Orange Line passengers than for CTA riders in general (44 percent) (*5*).

Ridership was heaviest during the morning peak (6 a.m. to 10 a.m. for this survey). Riders were surveyed in proportion to boardings by time of day, using the hourly data from the new turnstiles at the branch stations and annual observation of the Loop stations' daily patterns.

Prior Travel Mode

Nearly one-quarter (23.7 percent) of all riders formerly drove all the way to their destinations, got a ride, or had just started traveling in the corridor (new residents or new workers from automobile-owning households). The latter were assumed to represent potential automobile commuters as a part of the total market share diverted from automobiles (see Table 2). Sixty-five percent of all users formerly used the rather extensive diagonal bus service in the corridor, which focuses on radial service to downtown Chicago. A surprisingly large group (8 percent) used other CTA rapid transit lines, most likely the Red Line to the east and the Blue Line to the north. Very few had used the commuter rail network, Metra (2 percent), reflecting the low level of Metra service convenient to this corridor.

This level of automobile diversions, about 25 percent of line ridership, is consistent with the original ridership forecast of the 1982 alternatives analysis, although the total ridership on the Orange Line currently falls short of opening-day forecasts by about 35 percent. This result reflects significant changes experienced nationwide in the ability of transit to compete with the automobile over the last

TABLE 1 Transit Rider Trip Purpose: 1994

Trip Purpose	Commuter Travel Market			
	Core	Secondary	Tertiary	Total
Work	66.6%	58.8%	71.1%	60.6%
School	12.8%	16.6%	15.4%	13.6%
Work-Related	5.7%	4.4%	5.4%	6.4%
Work, Multiple Response	3.1%	4.3%	0.0%	3.4%
Airline Travel	0.1%	1.5%	6.5%	3.3%
Shopping	2.4%	2.6%	1.6%	2.2%
Social	4.9%	4.8%	1.9%	5.0%
Other	4.0%	6.0%	3.4%	4.9%
Non-Work, Multiple Response	0.4%	1.0%	0.7%	0.7%
	100.0%	100.0%	100.0%	100.0%

TABLE 2 Prior Mode Used by Transit Riders: 1994

Prior Mode	Commuter Travel Market			
	Core	Secondary	Tertiary	Total
Transit				
CTA Bus	75.2%	68.9%	50.4%	62.8%
CTA Rapid Transit	4.8%	7.5%	13.7%	8.3%
Metra	0.6%	2.2%	8.8%	2.3%
Auto				
Drove All the Way	9.2%	11.3%	13.7%	11.4%
Got a Ride	3.6%	4.4%	4.0%	4.7%
Auto, Multiple Response	2.2%	1.1%	2.5%	1.9%
Taxi	0.0%	0.0%	0.0%	0.3%
Just Started/New	2.4%	3.0%	5.5%	5.4%
Other	2.0%	1.6%	1.4%	2.6%
	100.0%	100.0%	100.0%	100.0%

decade. Transit's market share has steadily decreased, competing against a base of increasing automobile ownership and trip-making rates (*6,7*). Nevertheless, the Orange Line's October 1994 ridership levels of 37,500 daily rides represents a 43 percent gain over its first month, and compares quite favorably with new starts of other rail lines across the country (*8*).

One of the primary variables influencing the Orange Line's success in attracting former automobile travelers is comparative travel time. As indicated in Table 3, the Orange Line provides significantly faster service, with more reasonable waiting times, than predecessor express and local bus routes. In the morning peak it is 33 to 39 percent faster than express bus service, and 41 percent faster

TABLE 3 Travel Time Comparison: Orange Line Versus Former Bus Services

Sample Bus & Rapid Transit Trip	AM Peak (6-9 AM)				Midday (Noon-3 PM)			
	Sched. Wait Time (min.)*	Sched. Travel Time (min.)	Combined Travel Time (min.)	Percent Time Savings, Orange Line	Sched. Wait Time (min.)*	Sched. Travel Time (min.)	Combined Travel Time (min.)	Percent Time Savings, Orange Line
Midway Airport Station to Downtown (State/Lake Station)								
Orange Line	3.3	31.0	34.3	--	5.0	31.0	36.0	--
99M Express Bus	10.0	43.6	53.6	36.0%	--	--	--	--
Pulaski Station (Pulaski/Archer) to Downtown (State/Lake Station)								
Orange Line	3.3	28.0	31.3	--	5.0	28.0	33.0	--
162 Express Bus	7.5	39.0	46.5	32.7%	--	--	--	--
62 Express Bus	7.5	43.5	51.0	38.6%	15.0	36.0	51.0	35.3%
62 Local Bus	3.0	49.9	52.9	40.8%	3.3	46.0	49.3	33.1%

*Based on 1/2 of the average minutes between scheduled service frequencies.

than local bus service. Because of the congested operating conditions on the Stevenson Expressway, the Orange Line travel time from Midway Airport is roughly equal to or slightly better than automobile freeway travel time to the Chicago Loop. These relative travel-time gains were critical to the modal-utility values employed in the ridership forecasts made in 1982 (*1*), and indicate that the service-quality gains that were initially planned are being realized.

Access Mode

The most frequent mode of access to the Orange Line is bus (41 percent) followed by walking (26 percent) (Table 4). A surprisingly high 13 percent use the Park & Ride lot (and 11 percent use the Kiss & Ride dropoff point), indicating that many people park on neighborhood streets as well as in the Park & Ride lots that are at several stations. Park & Ride lots at three of the last four stations along the line receive considerable use, particularly the last two at the Midway and Pulaski stations (300 spaces each), which fill up early in the morning peak. Bus access includes both Pace and CTA bus routes, both of which have experienced ridership growth concomitant with the Orange Line's growth (*3*).

RIDERSHIP TRENDS

Ridership started at 26,200 each weekday in November 1993 and climbed to 37,500 by the end of October 1994. As indicated previously, that represents a 43 percent gain over 11 months, which is a rousing start for this new line. The upper line on Figure 2 shows total line boardings at all 16 stations. The lower line shows boardings at the eight branch-line stations only, excluding the central business district stations. (Note: the survey data on which these figures are based were collected in early March 1994, when total ridership was 32,000 each weekday.)

Boardings by station, shown in Figure 3, come directly from the new fare-collection turnstiles, which send registrations by fare type to a central computer each day. The new registration equipment at the branch stations has eliminated manual data entry, an improvement that speeds receipt of the counts by 3 weeks. Midway and Pulaski are the busiest branch stations, accounting for 50 percent of all branch station boardings. They see about 5,000 to 6,000 riders entering each day, with Midway Station alone typically accounting for 28 percent or more of branch boardings since the July 3, 1994 bus-route restructuring.

Air Quality Impact

On the basis of the survey results reported earlier that studied mode of travel, comparisons were made between actual bus and rail ridership statistics for the corridor. The first 2 weeks of February 1993 and February 1994 were selected as a baseline. Bus ridership on the ten diagonal routes serving the corridor fell 21,400 over those 12 months (from 45,900 on an average weekday to 23,800, adjusted for an overall system ridership loss that was discounted). Figure 4 summarizes these prior mode percentages, applied to an Orange Line average weekday ridership of 30,300, for the first 2 weeks in February 1994.

Similar analyses were conducted for June 1994 and October 1994 (see Figure 4). The following assumptions were made: Metra or other ridership would hold at 1,600 daily weekday trips diverted; CTA rail ridership (other lines) diverted would increase slightly, from 2,600 to 2,800 weekday trips; and 1,700 lost bus trips, assumed to have reverted to some form of automobile travel, would decrease to 1,500. Five of the parallel diagonal bus routes were eliminated, leaving only five routes continuing to provide service by October 1994.

Based on these assumptions and bus service changes, Figure 4 indicates that automobile diversions to the new Orange Line increased from 21.1 percent in February 1994 to 28.3 percent in October 1994. In February these new transit riders represented a growth of 19.3 percent in corridor transit trips; by October this increase was 31.0 percent. This represents an increase from an estimated 3.2 percent growth in CTA corridor market share, for transit work trips in February (from 16.4 percent to 19.6 percent) to an estimated 5.1 percent growth in CTA corridor market share by October (from 16.4 percent to 21.5 percent).

TABLE 4 Transit Rider Mode of Access Versus Trip Purpose

Mode of Access	Trip Purpose					
	Work	School	Work-Related	Airline Travel	Non-Work	Total
Transit						
CTA or Pace Bus	40.9%	51.5%	21.1%	13.0%	42.3%	40.7%
CTA Rapid Transit	3.6%	7.4%	8.5%	16.5%	7.0%	5.5%
Metra	0.1%	0.4%	1.3%	1.7%	0.0%	0.3%
Auto						
Park & Ride	16.3%	6.4%	13.0%	0.0%	7.9%	13.0%
Dropped Off	12.2%	4.8%	10.8%	5.8%	10.4%	10.6%
Multiple Response	0 .4%	1.7%	2.2%	1.6%	0.0%	0.7%
Walked	24.5%	27.0%	24.1%	41.1%	30.4%	26.1%
Other	2.0%	0.8%	9.0%	20.3%	2.0%	3.1%
	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%

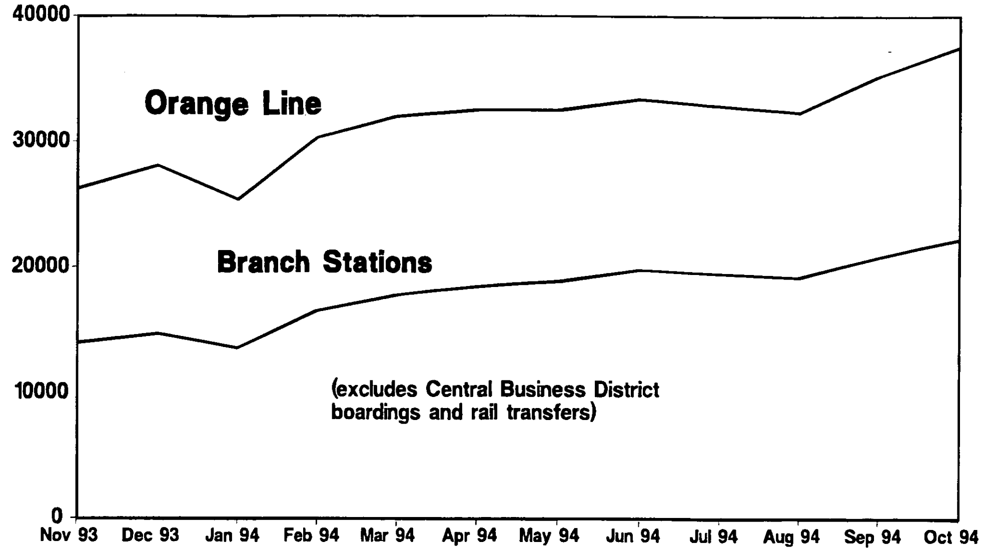

FIGURE 2 Orange Line—entering traffic (average weekday, 1993–1994).

Figure 5 summarizes the air-quality improvement implications of these former automobile travelers diverted to the Orange Line for each of the three observation points during 1994. An analysis method was developed that relies on the rider survey, transit boardings in the corridor, and Loop-bound transit-trip counts. No standardized method to estimate air-quality benefits of new rail lines was known, a topic worth consideration for uniform evaluations within a region and nationwide. The number of automobile vehicle kilometers that were avoided because the Orange Line captured former (and potentially new) automobile trips is indicated, based on a survey-derived 18.1 km (11.3 mi) average O-D trip length. Trip distances for former automobile trips were calculated using an algorithm relating O-D address locations to the grid street network in the survey analysis. Figure 5 also indicates the number of cold starts avoided, assuming one cold start for every automobile trip diverted to transit (ignoring possible automobile driver versus passenger differences).

Figure 5 also indicates an adjustment for net counterbalancing of air-quality impact, taking into consideration automobile access to transit by new or shifted Orange Line riders. In this calculation, any automobile access to past CTA service was ignored, assuming that all automobile access trips are new, making a new impact, and not just a continuation of past behavior by shifted riders. For example, those who may have driven to an Archer or Narragansett express bus are not considered. Had they been, they would have lessened somewhat the impact of new automobile access trips. For simplicity, the March 1994 survey result of 13.0 percent of weekday boardings representing travelers using the Park & Ride lots (or the Kiss & Ride dropoff points) was assumed to hold constant with ridership growth.

In fact, limited parking at the outermost two stations and the imposition of neighborhood parking restrictions near several stations may indicate an overestimate of this counterbalancing subtraction of automobile access to transit vehicle kilometers and cold starts avoided. The estimate of air-quality improvements achieved by October 1994 may be somewhat low. A survey-derived average length of automobile access trips of 6.4 km (4.0 mi) was used in the calculations.

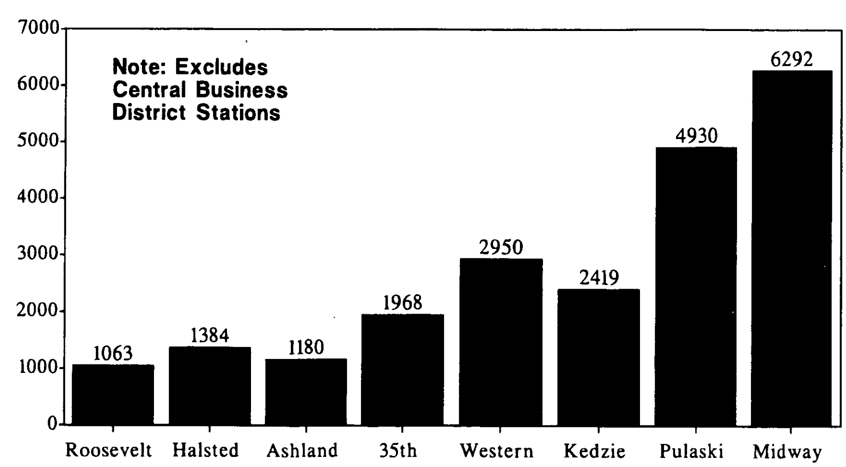

FIGURE 3 Orange Line—entering traffic (average weekday, October 1994).

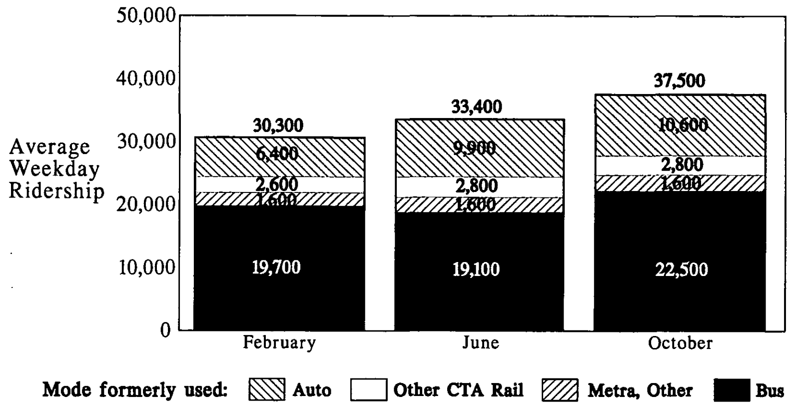

FIGURE 4 1994 Orange Line ridership growth.

Figure 5 indicates that by October 1995, a total of 5,700 average weekday cold starts and 160,500 average weekday automobile vehicle kilometers were being avoided through use of the Orange Line. These significant impacts indicate a positive contribution to air quality in the service corridor.

IMPORTANCE OF CONSISTENT SERVICE QUALITY AND EFFECTIVE MARKETING

The significantly improved service quality offered by the Orange Line was the key factor in attracting both former bus riders (many of whom are required to make a transfer, as compared with their former one-seat bus ride) and former automobile travelers. As a part of establishing a positive overall image for the line and building significant ridership from opening day a major marketing campaign was deemed by CTA management an essential undertaking (*9,10*). Although it is not possible to indicate separately that portion of additional ridership that could be directly attributed to marketing efforts, the rider survey also established clearly that CTA's marketing efforts reached most Orange Line riders and helped contribute to their "conversion" to rail transit.

Even before a marketing program was formulated, CTA Service Delivery staff conducted a series of community forums over the summer and early fall of 1993. The purpose of the forums, held in cooperation with local community organizations in the market area, was to alert residents to the forthcoming line, outline its basic service features, and answer questions about changes in overall transit service. Of particular concern to many residents were proposed changes to the bus service to which they had become accustomed. In fact, for that portion of riders who still expressed preference for express bus service, explanations were necessary to indicate the advantages (and disadvantages) of the new rail line.

CTA's CMAQ-funded marketing campaign was one of the largest CTA has ever undertaken, using almost all paid media. The line's opening was also well-reported on television news. Most riders (about four in five) saw the paid promotions. The "free" media—television, radio, or print news reports—were seen or heard by somewhat less than one-half of surveyed riders. And, most importantly, new riders saw the paid promotions; about three-quarters identified a billboard, print advertisement, or radio advertisement they had seen.

Sources of Riders' Information

Orange Line riders were asked in the survey to indicate how they had seen or heard about the Orange Line before riding it. Answers were divided into three groups: advertising, news accounts, and other sources (Table 5).

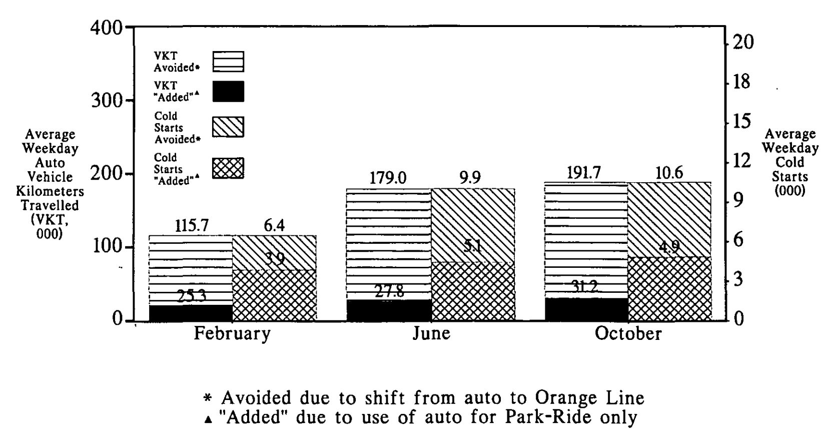

FIGURE 5 Air quality improvement implications.

TABLE 5 Sources of Information About Orange Line

Ads (79%)		News Accounts (44%)		Other Places (49%)	
14%	Magazines	29%	Television	37%	Friends
32	Radio	20	Radio	21	Family Members
43	Newspapers	25	Newspapers	22	Co-Workers
43	Billboards	6	Magazines	10	CTA Employees
63	CTA Buses			4	Other
43	CTA Train Stations				

NOTE: Respondents could mention more than one information source. The total percentage for each of the three categories is consequently higher than for any one of them, since multiple mentions were given. 1,858 respondents.

CTA's advertising and promotional campaign clearly had a major impact on Orange Line riders, because 79 percent of them mentioned at least one of the various promotional efforts. Fewer than half of all riders mentioned news accounts (44 percent) or other sources, such as friends and family (49 percent).

The single most successful method for informing CTA riders about the Orange Line was car cards on CTA buses, noticed by 63 percent of Orange Line riders. Other successful methods included:

- Similar advertisements at CTA train stations (seen by 43 percent of Orange Line riders),
- Billboards along the Stevenson Expressway and elsewhere (seen by 43 percent),
- Newspaper advertisements (seen by 43 percent),
- Radio advertisements (heard by 32 percent), and
- Magazine advertisements (read by 14 percent).

New Rider Profile

Further stratification of survey results for the one-quarter who were new riders was undertaken as a guide to future marketing efforts for the Orange Line, to be carried out in 1994 and 1995.

The 23.7 percent of survey respondents who represented new riders differed from other survey respondents in several ways.

- Work and school were less significant as trip purposes, accounting for 62 percent of new riders versus 77 percent of shifted riders. To and from a work-related activity increased from 5 percent for shifted riders to 10 percent for new riders. Airline travel was also an important trip purpose for new riders, accounting for 9 percent, versus 2 percent for shifted riders.
- Park & Ride was more important as a mode of access, accounting for 25 percent of new riders versus 10 percent of shifted riders, whereas CTA or Pace bus access was 52 percent of shifted riders compared to 28 percent of new riders. Fourteen percent of new riders got a ride, compared with 10 percent of shifted riders, and 28 percent walked, compared with 26 percent of shifted riders.

These results match expectations from the Midway Line Market Potential Survey of 1992 (*4*). In that survey people who did not use transit said they were more likely to gain access to the line by automobile. Nevertheless, over one-half of new transit riders rode the bus or walked to the Orange Line.

- Most new riders (52 percent) used to drive all the way, 22 percent used to get a ride, and 25 percent started making this trip since the Orange Line opened.
- Eighty percent of Orange Line riders who shifted from other transit services formerly rode buses, 11 percent rode another CTA rail line, 3 percent took Metra, and 6 percent took other modes.
- New riders were more likely to be male (56 percent versus 44 percent of shifted riders). The number of female riders declined correspondingly.
- More whites (68 percent) and fewer Hispanics (14 percent) were represented among new transit riders, as compared with 59 percent and 24 percent, respectively, among shifted riders.
- Automobile ownership was somewhat higher for new users, with 42 percent classed as zero- or one-auto households and 54 percent classed as two- or three-automobile households, versus 55 percent and 41 percent, respectively, of shifted riders. This is an interesting commentary on the increased success of rail over bus in attracting transit users.
- Combined household income was higher for new users. Only 28 percent reported incomes under $30,000 (compared with 42 percent for shifted users), whereas 23 percent (compared with 13 percent) reported incomes over $60,000.

Sources of Information for New Riders

New transit riders, like riders shifted from other transit, learned of the new line from various promotional materials, rather than by observing the line's construction. Because transit ridership typically turns over 15 to 20 percent every 12 to 18 months or so, it is of value to know whether new trip-makers (who responded on the survey, "just started making this trip") learned about Orange Line service from a different source than did those traveling by automobile who made the change to rail transit. About 5 percent of all respondents were making a new trip in the corridor; these riders represented about one-fifth of the overall market of new transit riders.

The single most successful method of informing CTA riders about the Orange Line was car cards placed on CTA buses, noticed by over half of new Orange Line riders. Presumably these signs were noticed during earlier (perhaps infrequent) CTA bus rides,

other than the ride surveyed in March. This was similar for both trips formerly made by automobile and new trips.

- Riders making new trips were less likely to have seen advertisements at CTA train stations (20 percent) than were former auto travelers (31 percent).
- Billboards along the Stevenson Expressway and elsewhere were seen by both former automobile users (40 percent) and those making new trips (36 percent).
- Newspaper advertisements were seen by 38 percent of former automobile travelers and 32 percent of those making new trips.
- Radio advertisements were heard by 35 percent of former automobile users and 27 percent of those making new trips.
- Magazine advertisements were read by 16 percent of former automobile travelers and a similar 15 percent of those making new trips.

CONCLUSIONS: EARLY LESSONS LEARNED

Improved Service Levels

- To divert a significant number of automobile users to transit, competitive travel times are essential, both in relation to conventional mixed-traffic bus service (even express) and automobile travel.
- Even more important, potential riders must perceive travel times favorably, particularly in terms of schedule reliability and wait time, smooth, uninterrupted interstation vehicle flow, and efficient passenger movement through stations.
- New grade-separated and express transit service must get off to a good start, both in terms of press coverage and in having all the operational bugs worked out before opening day.
- Transit must not only initially establish a positive image, but maintain good service as a reliable, dependable feature, especially for new riders.
- "Extra effort" should be a major training theme for employees who inaugurate new service, as a part of building transit-ridership habits on the part of the market served.

Marketing and Community Outreach

- Good paid promotion campaigns, using print media, billboards, radio, and in-vehicle advertising, can be very effective in reaching potential riders and should be employed as a part of a creative marketing campaign.
- Good press coverage up to, on, and after opening day can also play a major, although not determining, role in building a favorable image in the community for major transit improvement projects. Every effort should be made to establish a good relationship with the press as a part of inaugurating new service.
- Preopening community forums, in which transit agency representatives explain the features of major new service improvements—particularly addressing the specific changes in present service—can help increase rider awareness and acceptance on opening day.

Attracting New Riders

- Park & Ride facilities, particularly at outlying stations, must be large enough and convenient enough for a potentially sizable portion of new riders, in spite of air-quality-related cold-start issues.
- Park & Ride can be controversial as an access mode, not only because it compromises air-quality gains achieved by the shift to transit, but because it can create neighborhood frictions when overflow demand spills out onto local residential streets near rail stations whose Park & Ride facilities may be too small or nonexistent.
- The most important promotional medium for reaching potential new riders, as well as achieving the shift from express bus to rail, was bus car card advertising. Because of the extensive bus coverage in the southwest corridor and the central area before the opening of the Orange Line, even occasional bus riders saw the advertisements.
- Billboards, newspaper advertisements, and radio spots were also effective marketing tools, and should be coordinated in a common-theme, multimedia marketing program, targeted particularly at new riders.
- For opening day, the basic Orange Line message was "Rail Service is Here." Later marketing campaigns can target specific submarkets, with varied themes, based on research on the rail line's appeal.

REFERENCES

1. *Alternatives Analysis/Draft Environmental Impact Statement for the Southwest Transit Corridor.* Chicago Department of Public Works, Bureau of Transportation Planning and Programming, Sept. 1982.
2. *Orange Line Travel Survey.* PMR-x94035. Chicago Transit Authority, Market Research Department, May 1994.
3. LaBelle, S. J. CTA's Orange Line: A Preliminary Evaluation. Presented at the 1994 Chicago Metropolitan Conference on Public Transportation Research, University of Illinois at Chicago, June 1994.
4. Marketing Strategy & Planning, Inc. *Midway Line Market Potential Survey.* SP92-06. Chicago Transit Authority, June 1992.
5. *1990 Traveler Behavior and Attitudes Survey.* PR91-10. Chicago Transit Authority, Planning and Research Department, Sept. 1991.
6. Rosetti, M. A. and B. S. Eversole. *Journey to Work Trends in the United States and Its Major Metropolitan Areas.* National Transportation Systems Center, U.S. Department of Transportation, Cambridge Mass., Nov. 1993.
7. Pisarski, A. E. *New Perspectives in Commuting.* FHWA-PL-92-026. FHWA, U.S. Department of Transportation, July 1992.
8. Light Rail Transit: Planning, Design, and Operating Experience. In *Transportation Research Record 1361*, TRB, National Research Council, Washington, D.C., 1992.
9. Flannelly, K. J., et al. Direct Comparison of Commuters' Interests in Using Different Modes of Transportation. In *Transportation Research Record 1321*, TRB, National Research Council, Washington, D.C., 1991.
10. Silkunas, S. Customer Satisfaction: The Next Frontier, Presented at TRB Annual Meeting, Washington, D.C., Jan. 1993.

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Street-Running Rail Transit: A Historical Perspective

HERBERT S. LEVINSON

The strengths and weaknesses of street-running rail transit are presented, along with examples of where streetcar lines, inter-urban electric railways, and rapid transit lines have relocated sections of route to private rights-of-way (ROWs) to improve safety, travel time, and reliability. It is important to avoid (or minimize) street-running today because of more potential conflicts among autos, buses, pedestrians, and trains, and because of a need to maximize speed and reliability. Street-running in the central business district generally should be viewed as the first stage that leads to incremental transitions to reserved ROWs. The goal is to plan for and provide off-street or reserved operations as soon as possible and as resources permit. A historical overview of the experiences of various transit systems are presented and techniques are identified that may be applicable to current rail transit development.

Light rail transit (LRT) is growing in popularity as a means of improved public transport. The ability of light rail vehicles (LRVs) to operate in a broad range of environments, both on and off-street, and their appeal have made them an attractive transport option for many urban areas.

Several of the newer LRT systems in the United States and Canada involve some street-running, especially in city centers. This street-running (in transit malls, reserved lanes, and within median reservations) reduces construction costs and complexity. At the same time it introduces LRVs into an already complex environment and makes trains more susceptible to delays and interferences.

A historical perspective of street-running rail transit is presented with descriptions of the strengths and weaknesses of street-running. A series of case studies illustrates how streetcar and light rail systems, inter-urban railways and rapid transit lines have reduced or eliminated street-running over the years. Finally, emerging implications for rail transit planning are discussed.

OVERVIEW OF STREET-RUNNING

Street-running includes rail transit lines that operate in mixed traffic, preferential lanes, or transit malls. It also includes low-speed (i.e., less than 25 mph) operations in median reservations. These non-exclusive and semi-exclusive rights-of-way (ROWs) are usually found in the central business district (CBD) and the area around it.

The strengths and weaknesses of street-running versus grade-separated ROWs reflect the tradeoffs between lower initial costs and longer travel times. Key comparisons follow.

Street-running rail transit significantly reduces initial construction costs and the time needed to place a system in service. Costs for surface lines are about one-third of those for aerial lines and one-ninth of those for subways. This is an important consideration, particularly in "medium-sized" urban areas. The lower construction costs may reduce the costs-per-rider and thereby improve the cost-effective index. Thus, they may keep systems financially or economically infeasible.

Another advantage of street-running is that it makes full and perceivable use of available public ROWs. In some cases, the system becomes a catalyst for needed street traffic and pedestrian improvements.

However, street-running introduces another somewhat disparate element into an already complex traffic stream. Trains must interact with vehicle traffic and pedestrians. This results in lower speeds, less reliability, reduced capacity, and more accidents.

The combined effects of dwell times at stations (stops) and red times at traffic signals result in a travel time loss of about 3 to 5 min per mile (2 to 3 min per kilometer). This could reduce passenger attraction and increase operating costs, especially when several kilometers (miles) of street-running are required.

The greater travel times may increase operating and fleet costs depending on the amount of time lost and the service frequency. Thus, 4.8 km (3 mi) of street-running with a time loss of 4 min per mi (2.5 min per km) would require one additional train set for headways of 10 to 12 min. Traffic signal preemption can reduce delays at signals, but its extent is limited in most city centers because of the need to clear pedestrians to accommodate intersecting bus routes and, in some cases, heavy cross traffic. The constraints of signal network coordination requirements further limit the signal preemption opportunities in downtown settings.

During peak loading periods, trains are more likely to bunch unless the intervals between them are long. Heavy passenger loadings might cause a train to "miss a green light," and fall behind its leader, with a cumulative effect.

LRV capacities are limited in that (*a*) the train consist length is normally governed by the street block spacing; (*b*) the number of trains per track per hour is limited not only by dwell time and train clearance requirements, but also by the time required by cross street traffic; and (*c*) train turns from one street to another may require a special signal phase, thereby limiting the amount of green time available for trains. This poses a serious constraint where train turns are located adjacent to a major passenger stop.

System safety is reduced because the greatest number of accidents occur along street-running segments of LRT lines. Street-running accounts for about 17 percent of the route miles and 89 percent of the accidents along Howard Street in Baltimore; 8 percent of the route miles and 75 percent of the accidents along the 7th Avenue Transit Mall in Calgary; 25 percent of the route miles and 79 percent of the accidents along the Los Angeles Blue Line; and 10 percent of the route miles and 57 percent of the accidents along 12th Street in Sacramento (*1*).

40 Hemlock Road, New Haven, Conn. 06515.

Left turns across oncoming train tracks is a commonly reported problem. Contra-flow LRV operations pose problems related to motorist and pedestrian expectancy. The intermingling of pedestrians and trains at stops, on turns, in pedestrian precincts, and at intersections creates a new set of conflicts.

Street-running often poses additional problems to general traffic and pedestrians. The tracks and stations may be barriers to pedestrians crossing the street; there is less capacity for road traffic; and goods delivery and service vehicle access is more limited. Left turns often must be prohibited or given exclusive phases and right turns are often problematic with side-running.

Street-running through the city center is somewhat analogous to building an express highway on both approaches to the CBD with the central section consisting of city street operations with traffic signal control.

EFFORTS TO REDUCE STREET-RUNNING

The elimination of street-running dates back to the early years of electric traction. A literature review identified 18 examples of street railway, inter-urban, or rapid transit lines that removed all or part of their operations from city streets (Table 1). Most of these examples were found in the larger metropolitan areas. The relocations were designed to reduce or relieve streetcar congestion, remove terminals from streets, increase reliability, provide faster entry into the city by cutting running times (and thereby operating costs), and in one instance to allow conventional freight car operations. Rapid transit lines were removed from streets when the growth of surrounding areas made street-running no longer feasible.

Street Railways

Sections of street railways in Boston, Cleveland, Newark, Philadelphia, Pittsburgh, Rochester, and San Francisco were placed in subway or private ROWs, often to eliminate the congestion caused by the streetcars themselves.

Boston

The congested traffic conditions in downtown Boston in the latter years of the 19th century reached acute dimensions. "On Tremont Street during the afternoon rush hour, the cars were packed so close together that one could almost walk from Scollay Square to Boylston Street on the car roofs" (*2*) (Figure 1). These conditions led to the construction of the Tremont Street Subway, which opened in 1897. This was the first rail transit subway in North America. The initial sections ran from Park Street to the Public Garden on Boylston Street, and to Tremont and Pleasant streets. In 1898, the subway was extended northerly from Park Street to North Station. The Lechmere Viaduct to Cambridge was opened in 1912, and in 1914 the Boylston Street incline in the Public Garden was relocated to the center of Boylston Street (*3*).

The western extension to Kenmore Square and beyond was completed in 1925 and 1932 respectively. In 1941, the Huntington Avenue subway opened, and the Boylston Street trolley incline was discontinued, eliminating all street-running in the center of Boston ("Boston Proper").

Post-World War II improvements by the Massachusetts Bay Transit Authority and its predecessor agency, the Metropolitan Transit Authority, continued to reduce on-street operations. The Riverside extension was built on the old Highland Branch railroad ROW. In 1962, the streetcar routes from Broadway and Tremont streets were discontinued. More recently in the 1980s, revenue service on the street-running line to Watertown has been abandoned, and the tracks are being removed. As of mid-1994, the only remaining nonsegregated street-running is along sections of Huntington Avenue and South Huntington from Brigham Circle to Heath Street. On-street service between Heath Street and the Arborway has been discontinued to improve reliability along other parts of the route. This service is provided by bus.

Newark

Newark also took an incremental approach to eliminating street trackage in its downtown area. Its "Four Corners" intersection of Broad and Market streets was once one of the busiest trolley intersections in the United States. In 1910, as many as 525 streetcars passed through this intersection during a single peak hour, and trolley backups of as many as 20 cars were common (*4*).

To alleviate this congestion, the New Jersey Public Service Company redesigned and rebuilt downtown streetcar routes to divert streetcars from congested areas. This reconstruction included a large off-street terminal, built in 1916, in which a short subway in Cedar Street could load and lay over cars from public streets to the basement and second floor of the new terminal (D. Phraner and S. Kashin, personal communication). The City Subway, built in 1935 to serve cars from the west, now operates a single 6.8-km (4.2-mi.) line, partly in an abandoned canal bed. Average daily ridership exceeds 12,000, and overall speeds are approximately 20 mph.

Philadelphia

Street traffic congestion prompted the Philadelphia Rapid Transit Company to develop the parallel Market Street rapid transit and surface-car subways.

The original rapid transit line was opened between 69th and 15th streets in 1907 and was extended to second-Port Street in 1908. An elevated extension was built to South Street and Delaware Avenue in 1908, but was discontinued in 1939. Between the Schuylkill River and City Hall, a four-track subway was built. Subway-surface cars have used the outer two tracks since 1905 (*5*).

In 1955 both the rapid transit and surface-car subways were extended west to about 45th Street.

Pittsburgh

Streetcar subways were proposed for more than 75 years to relieve streetcar congestion in the Golden Triangle. (By the mid-1920s almost 700 streetcars left the 0.5-sq-mi^2 (1.3-sq-km^2) downtown area over nine routes; 150 used the Smithfield Street Bridge) (*6*). A 1.6-km (mile-long) subway was opened in 1958, modern LRV cars were acquired, and downtown street-running was eliminated. The subway connects the area's remaining trolley lines that serve the South Hills area mainly via the Mount Washington Tunnel. These lines, which run largely on private ROWs, continue to be upgraded.

TABLE 1 U.S. Electric Railways That Eliminated Street-Running

CITY AND/OR SYSTEM	LOCATION	YEAR
STREET RAILWAYS		
BOSTON	PARK ST.- BOYLSTON ST. SUBWAY	1897-1898
	BOYLSTON SUBWAY EXT. TO KENMORE SQ.	Beyond 1925-1932
	HUNTINGTON AVE SUBWAY	1941
NEWARK	CEDAR STREET SUBWAY	1917
PHILADELPHIA	CITY SUBWAY	1935
	MARKET ST. SUBWAY, 15TH TO SCHUYKILL	1905
	SCHUYKILL TO 45TH	1955
PITTSBURGH	DOWNTOWN SUBWAY	1985
ROCHESTER	MAIN ST. SUBWAY	1927
SAN FRANCISCO MUNI	MARKET ST. RELOCATION TO SUBWAY	1972
SHAKER HEIGHTS (CLEVELAND)	SHAKER SQUARE TO UNION TERMINAL	1930
INTERURBAN ELECTRIC RAILWAYS		
CHICAGO, AURORA AND ELGIN		1934
CHICAGO NORTH SHORE AND	SKOKIE VALLEY BYPASS	1926
MILWAUKEE RAILWAY	WINNETKA GRADE SEPARATION	1939-1940
CHICAGO SOUTH SHORE AND SOUTH BEND RAILROAD	EAST CHICAGO BYPASS	1956
COLUMBUS, DELAWARE AND MARION	WORTHINGTON BYPASS	1923
ILLINOIS TERMINAL RAILROADS	FREIGHT BELT LINES IN CHAMPAIGN, URBANA, DECTATUR, SPRINGFIELD, EDWARDSVILLE	1915-1937-
	ST. LOUIS ELEVATED & SUBWAY TERMINAL	1933
INDIANA PUBLIC SERVICE CORPORATION	WABASH BYPASS	1931
THE MILWAUKEE ELECTRIC RAILWAY AND LIGHT CO.	SUBURBAN AND INTERURBAN ENTRIES INTO MILWAUKEE FROM SOUTH, AND WEST, INTO KENOSHA.	1928-1932
PACIFIC ELECTRIC RAILWAYS (LOS ANGELES)	ELEVATED APPROACH TO MAIN ST. TERMINAL	1917
	HILL ST. TUNNEL	1925
	LINE IN HOLLYWOOD FREEWAY MEDIAN THROUGH CAHUERGA PASS	1949
WASHINGTON, BALTIMORE AND ANNAPOLIS	RELOCATE TO B&O CAMDEN STATION	1922
RAPID TRANSIT LINES		
BROOKLYN RAPID TRANSIT	CULVER AND WEST END LINES 36TH ST.-CONEY ISLAND	1919 AND 1917 RESPECTIVELY
CHICAGO & OAK PARK ELEVATED	RELOCATING RANDOLPH ST. LINE TO SOUTH BOULEVARD	CIRCA 1901

SOURCE: Compiled by Herbert S. Levinson and George Krambles.

Rochester

To reduce downtown congestion, Rochester opened a streetcar and inter-urban subway in the abandoned bed of the Erie Canal in 1927. Inter-urbans of the Buffalo, Lockport, and Rochester Railway; the Eastern Rochester and Rapid Railway; and the Rochester and Syracuse operated in the subway until about 1931. Local trolley operation in the Municipal Subway continued until 1956.

San Francisco

Streetcar and traffic congestion on Market Street in the downtown area has a long history. Four tracks were provided, two for the Market Street Railway and two for the Municipal Railway. Each track carried about 75 cars in the peak evening period of 5:00 p.m. to 5:30 p.m. Daily volumes on the western entrance to the downtown area exceeded 125,000 passengers in 1929 (*7*).

The combinations of heavy passenger boardings and alightings on both the inside and outside tracks; the short spacing between cars (20 to 30 sec); cross street interferences; and automobiles encroaching on tracks resulted in speeds that were less than 4 mph on sections of downtown streets during peak periods (Figure 2). "In some sections . . . it was . . ." possible to walk faster than the cars traveled (*8*). Minor accidents or unusual occurrences resulted in streetcars leaving the downtown area 5 to 10 min behind schedule (*8*). Two of the four tracks were removed after World War II when trolley or motor buses replaced streetcars on several routes.

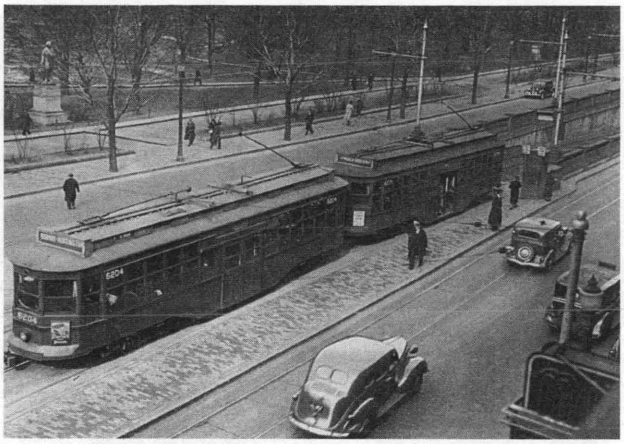

FIGURE 1 Boylston Street Incline (Boston) near the Public Garden, was used by Jamaica-Arborway subway-surface line until 1941. (From collection of Fred F. Freeman, reprinted from *Rapid Transit Boston Bulletin 9*, 1971, with permission).

FIGURE 2 Loading zone on Market Street, San Francisco, circa 1935 (*8*).

The Market Street streetcar subway, built in conjunction with Bay Area Rapid Transit and opened in 1972, is a culmination of a half century of proposals. Since then, all streetcar operation has been moved underground, although one set of tracks remains on Market Street. The city of San Francisco is re-establishing a single route on the surface along Market Street and the Embarcadero to reinforce tourism and supplement the subway lines, including the use of vintage trolleys.

The travel time between the Embarcadero and Powell Street stations (a distance of 1.9 km) (1.2 mi) was reduced from about 10 to 12 min to 4 min as a result of the subway operation.

Shaker Heights

The Shaker Heights Rapid Transit System (now part of the Greater Cleveland Regional Transit Authority) was initially built on open land by the Van Sweringen Brothers to encourage real estate development. The Shaker Boulevard Line was opened in 1909 and the Moreland Boulevard (Van Aken) Line was opened in 1920. Both lines were built within wide median reservations (*9,10*).

Access to downtown Cleveland was provided over the existing street railway network between 1909 and 1920. In 1920 a new line on an exclusive ROW was built from Moreland Circle (now Shaker Square) to 34th Street, where a ramp provided access to the downtown area via the existing streetcar lines. Operation into Union Terminal began in July 1930, thereby providing a 8-km (5-mi) high-speed, fully grade-separated entry into the city center; running times over this section have ranged from 10 to 13 min. These faster running times permitted short outer extensions while preserving the 1-hr round trip.

The line shares several kilometers with the Cleveland Rapid, as well as a new terminal in the new Tower City Development of Union Terminal.

Other Examples

Off-street routes and terminals were proposed or developed in other areas as a remedy for street-running. Some avoided complex intersections, such as Capital Transit's Du Pont Circle Subway in Washington, D.C. Some, like Cincinnati's subway, were started but never completed.

Inter-urban Electric Railways

Inter-urban railways frequently ran on city streets and shared slow streetcar tracks to reach their downtown terminals. The time lost in street-running was one of the inter-urban's major disadvantages, and it became severe as automobile traffic and curb-parking conflicts increased.

Accordingly, many of the systems serving large urban centers relocated their lines over the years to eliminate street-running. Street-running was eliminated on sections of the inter-urban railways serving Baltimore, Chicago, Los Angeles, Milwaukee, and St. Louis, as well as several lines in Indiana and Ohio. The reasons cited include (a) to provide a faster entry into the city center, (b) to eliminate slow or congested street running, (c) to remove the terminal from city streets and, (d) in the case of the Illinois Terminal Railroad, to make it possible to operate standard freight cars.

Chicago, Aurora, and Elgin Railroad

The Chicago Aurora and Elgin Railroad (CA&E) was one of the three high-speed lines that linked the Chicago Loop with surrounding areas. The line opened in 1902 and 1903 between Laramie Avenue in Chicago and the Fox River Valley suburbs of Aurora, Batavia, and Elgin—about 65 km (40 mi) west of the loop. Direct entry into the loop was provided via the elevated lines in 1905. An extension to Geneva and St. Charles was opened in 1907.

Operation was mainly on private ROWs with third rail power collection. However, there was street-running in the Fox River Valley towns of Geneva, St. Charles, and Aurora. The West Chicago-Geneva-St. Charles Line was abandoned for lack of traffic in 1937. A private ROW and a new terminal replaced street-running in Aurora, the last on the CA&E, in 1939 (*11*).

Construction of the Congress Street Expressway in Chicago and the median strip rapid transit required surface operation of "L" trains in 1953. At this time, CA&E trains terminated at Des Plaines

Avenue. The loss of one-seat service to downtown Chicago coupled with the increase in auto ownership and deferred maintenance led to the termination of passenger service in 1957. Freight service was stopped 2 years later.

Chicago North Shore and Milwaukee Railway

The initial line between Milwaukee and Evanston was completed between 1891 and 1908. Street-running took place in Milwaukee, Waukegan, Winnetka, and Wilmette. In 1916, the Insull Interests acquired the railroad and began a decade-long modernization process. In 1919, direct entry was provided into the Chicago Loop via the elevated lines. A new terminal was built in Milwaukee from 1920 to 1921 and several blocks (1.1 km or 0.7 mi.) of street-running were removed (*12*).

The 42-km (26-mi.) Skokie Valley route was opened from Howard Street, Chicago to North Chicago Junction in 1926 as a high-speed bypass of the original Shore Line. This resulted in a 10- to 15-min time savings. Travel times for the 145 km (90 mi.) between the loop and downtown Milwaukee were reduced to 2 hr or less, including 12 min for 5 km of street-running in Milwaukee.

The North Shore Line cooperated with the parallel Chicago and Northwestern, and public agencies cooperated in a line relocation project through Glencoe, Winnetka, and Kenilworth in 1939 and 1940. The relocation eliminated more than a dozen grade crossings and several miles of street running.

However, street-running remained in Wilmette and Waukegan until the abandonment of the Shore Line route in 1955. Elimination of street-running in Milwaukee came with the complete abandonment of operations in 1963. The 8-km (5-mi.) Skokie Swift operation was established on the south end of the Skokie Valley Line by the Chicago Transit Authority (CTA) in 1964.

Chicago, South Shore, and South Bend Railroad

The 145-km (90-mi.) South Shore Line provides an excellent example of the incremental elimination of street-running over several decades. The line opened between Chicago and South Bend in 1909 and was substantially improved during the 1920s under Insull control. Trains entered Chicago over Illinois Central tracks that were electrified in 1927. They operated on city streets in South Bend, Michigan City, and East Chicago, Indiana (Figure 3) (*13*).

Street-running was eliminated in East Chicago in September 1956 when a new 8-km (5-mi.) cutoff was built alongside the Indiana Toll Road (Figure 4). The relocated line eliminated 32 rail and street crossings, thereby improving on-time performance and saving 3 to 4 min of running time.

The 3.5 km (2.2 mi.) of street-running in South Bend was eliminated in 1970 when a new terminal was built at Bendix, and the line to the original downtown terminal was discontinued. Within the last few years, the South Shore Line was extended northerly and then westerly to a new terminal at the South Bend Michigan Regional Airport. This extension is along mostly unfenced side-of-the street running with frequent grade crossings.

The street running in Michigan City remains a vestige of the inter-urban era. However, the Northern Indiana Commuter Transit District, the current operator, is planning a bypass around the city.

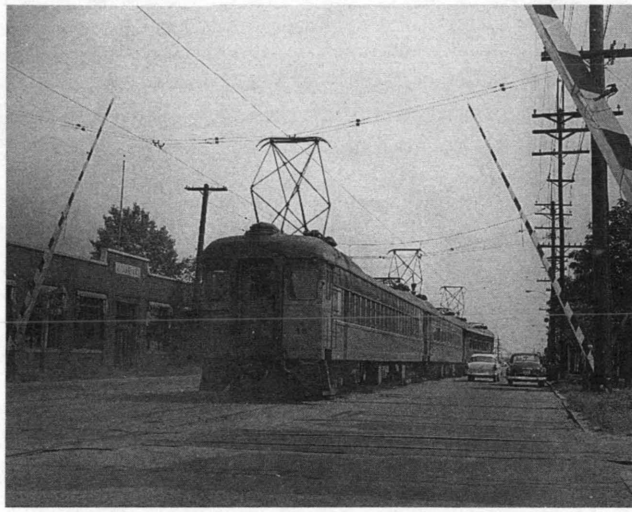

FIGURE 3 South Shore Line: street-running in Michigan City (old route), circa 1930 (from collection of George Krambles; used with permission).

Columbus, Delaware and Marion Railway

This 81-km (50-mi.) inter-urban, opened in 1903, was located mainly on a private ROW separated from the parallel highway by a ditch and pole line (*13*). In 1923, 10.5 km (6.5 mi.) of its entrance into Columbus including a bypass around Worthington were relocated onto private ROWs. Passenger service was discontinued in 1933.

Illinois Terminal Railroad

The 645-km (400-mi.) Illinois Terminal Railroad System (initially, the Illinois Traction System) was the largest inter-urban railroad except for the essentially suburban Pacific Electric System. Its lines served St. Louis, Alton, Springfield, Peoria, Bloomington, Decatur, Champaign-Urbana, and Danville, and covered much of central Illinois. Unlike most inter-urbans, the line carried both passengers and freight with equal intensity and emphasis (*14*).

The original lines between Danville and Urbana were completed in 1901. By 1908, the entire system was in place. A new bridge over the Mississippi River was opened in 1910.

Street-running was common in many towns and cities along the route. Under the management of William B. McKinley, an Illinois congressman, freight belt lines were completed around Decatur, Springfield, Edwardsville, and Granite City between 1911 and 1913. These bypasses enabled freight trains to avoid city streets and to handle car load freight. Many 65-km (40-ft) radius curves limited the length and types of trains that could be accommodated. Some communities restricted freight trains between midnight and 6 a.m. (*14*).

An additional belt line was built in the Champaign-Urbana area in 1927 to eliminate street-running and to permit the interchange of freight cars with steam lines. This belt involved electrifying sections of Illinois Central and Wabash Railroad tracks (*15*).

An elevated approach to downtown St. Louis was completed in 1931, and a new St. Louis subway terminal opened in 1933. These improvements eliminated all street-running in St. Louis.

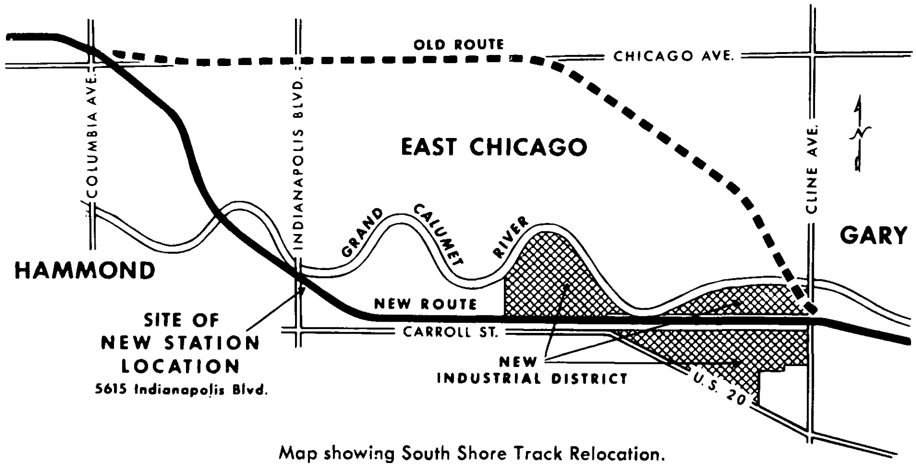

FIGURE 4 South Shore track relocation, Michigan City, 1956 (courtesy Chicago, South Shore, and South Bend Railroad).

Passenger service was eliminated by 1956, except for the Granite City-St. Louis streetcar line that remained until 1958. The various lines were then dieselized for freight service. The Norfolk and Western purchased the remaining freight lines and trackage rights in 1981.

The Milwaukee Electric Railway and Light Company

This 322-km system connected Milwaukee with Kenosha, Racine, Watertown, and Sheboygan. It was developed between 1895 and 1909. Street-running was common in these cities.

During the 1920s, the company initiated a $6 million improvement project to improve access into downtown Milwaukee. An 11-km (7-mi.) private ROW surface entrance for western lines with three and four tracks was completed between Eighth Street and West Junction by 1932. A 17-km (10.5-mi.) belt around south Milwaukee cut 30 min of travel time on the route to Racine and Kenosha. A similar project on the Sheboygan Line and a 0.8-km (half-mile) subway into the downtown terminal from the Western Line were never completed (*16*). Street-running remained on the approach to the downtown (off-street) Milwaukee terminal.

The West Side Line was used both by inter-urban trains and city streetcars. Speeds on the private ROW including stops averaged 48 km/hr (30 mph).

The various lines were abandoned between the 1930s and the 1950s. Service to Waukesha and Hales Corners was discontinued in 1951. [A serious accident in 1950 resulting insurance difficulties, and the loss of traffic contributed to the final abandonment (*13*)]. City streetcar service over the exclusive ROW continued until 1959. An interstate freeway was subsequently built over much of the ROW.

Pacific Electric Railway

The Pacific Electric (PE) Railway traces its origin to the Los Angeles-Long Beach Line built by Henry E. Huntington about 1905 where the Blue Line LRT trains now run. The system was extensively developed by 1915 when its 1 600 km (1,000 mi.) of track covered the entire metropolitan area and made it the largest inter-city electric railway system in the United States. The railway came under Southern Pacific control after a merger in 1911.

A large part of the system operated on private ROWs. These included the lines to Long Beach, Santa Ana, Newport Beach, and San Bernardino. However, there was considerable street-running on the Western District Lines leading out of downtown Los Angeles, in Hollywood, Santa Monica, Pasadena, Glendale, and in the downtown area itself.

The PE Lines were built largely ahead of the population at a time of low car ownership. Consequently, street-running posed relatively few problems at first, except in downtown Los Angeles. As traffic congestion increased, several sections of street-running in downtown Los Angeles were relocated.

To improve entry into the downtown area from the south, an elevated approach was built between San Pedro Street and the terminal at Sixth and Main in 1917. This left only a few blocks of street-running on San Pedro Street and Olympic Boulevard before reaching the four-track private ROW along Long Beach Boulevard. (The current Blue Line LRT has more street-running along Washington Boulevard and Flower Street than the PE approach to its former terminal.)

Two short tunnels were opened under Bunker Hill in 1909 to shorten running time for cars traveling to and from the west. One tunnel extended about 168 m (550 ft) from First to Temple, and the other almost 305 m (1,000 ft) from Temple Street to Sunset Boulevard (*17*).

A 1.6-km (1-mi.) subway for trains was built from a point near Glendale Boulevard and First Street to a terminal at Hill and Fourth streets in 1925 at a cost of about $5 million. The subway served trains for Hollywood, Burbank, and Van Nuys, removing these services from downtown streets. Travel times were reduced by about 5 min.

A further attempt to eliminate street-running was achieved in 1949 when a rail line was located in the median of the then six-lane Hollywood Freeway through Cayuenga Pass. This was the first rail transit line built within a freeway median.

A significant portion of PE passenger service was abandoned between 1938 and 1941 in response to a study by the California Public Utilities Commission. However, the high-density lines remained until after World War II (*18*).

After World War II, the inter-urban lines gradually disappeared. The Burbank and Hollywood Lines (and the Hill Street Subway) were abandoned in 1958, and the Hill Street Tunnel remains unused. The last line—to Long Beach—ceased passenger service in 1961. The Southern Pacific continues to operate dieselized freight service on portions of several lines (*7*).

Current plans to develop a regional light rail system incorporate many former PE ROWs. Downtown distribution will be via an extension of the Flower Street subway through the northern part of central Los Angeles.

Washington, Baltimore, and Annapolis

The Washington, Baltimore, and Annapolis (WB&A) was a high-speed, high-density inter-urban that connected Washington, Baltimore, and Annapolis. Its Washington-Baltimore main line was opened in 1908.

Beginning in 1921 and through the next year, a modern passenger and freight terminal was built north of the B&O Camden Station in Baltimore. This eliminated street-running and the use of an on-street terminal in Baltimore.

In March 1921, a new 3-block loop station was opened at 12th Street and New York Avenue in Washington D.C. This eliminated loading and unloading directly from the street. However, trains continued to use local streetcar tracks in Washington and took 30 min to reach the private ROW to Baltimore. Running times of the faster trains for the 65-km (40-mi) trip to Baltimore were reduced to 65 min, but still remained longer than that on parallel main-line railroads (*19*).

The long, slow trip to downtown Washington caused the WB&A to abandon its Washington service during the Depression. The line between Baltimore and Annapolis was reorganized as the B&A and continued to provide passenger and freight service until 1950 when passenger service stopped. Sections of this line form part of Baltimore's Central LRT that was opened in 1992. The LRT, unlike its predecessors, has extensive street-running along Howard Street in downtown Baltimore.

Rapid Transit Lines

Rapid transit systems were developed around the turn of the century in Boston, Chicago, New York, and Philadelphia to overcome the congestion and capacity constraints associated with surface transit. Similarly, the first 6.5 km (4 mi.) of Toronto's Yonge Street subway, which opened in 1954, replaced the slow and overcrowded Yonge streetcar line.

Rapid transit lines in outlying parts of Brooklyn and the Chicago area ran on the surface, often with overhead current collection. Four lines in Chicago (Douglas, Evanston, Ravenswood, and Skokie) still operate partly on the surface.

Two examples were found (in Southern Brooklyn and in Oak Park, Illinois) where rapid transit trains actually ran on the streets.

Brooklyn

Early rapid transit trains operated on several streets in Southern Brooklyn between 36th Street and Coney Island. Trains on the Culver Line ran along McDonald (Gravesend) Avenue from about 1900 to 1919 when the line was elevated. Trains on the West End Line ran along New Utrecht, Bath, and Stillwell avenues until 1916 to 1917, when the line was elevated as part of New York City's Dual Contracts program (Figure 5). Both lines, along with the Sea Beach and Coney Island lines, evolved from steam railroads serving the Coney Island area during the last part of the 19th century (R.A. Olmsted, personal communication).

Chicago

The Chicago and Oak Park (Lake Street) Elevated Line was extended on the surface of Austin Avenue and Randolph Street to about Wisconsin (Harlem) Avenue in Oak Park in 1899 (Figure 6). This street-running lasted about 2 years when the line was located to the immediate north on a separate ROW on the northern half of South Boulevard (*20*).

The CTA relocated the line from South Boulevard to the parallel Chicago and Northwestern Railroad embankment in October 1962 at a cost of $4 million. The relocation eliminated all at-grade crossings and the need to change from third-rail to trolley operations (*21*). The entire Lake Street Line, including the embankment, is currently under reconstruction.

The CTA and its predecessor agencies eliminated a considerable amount of rapid transit operations at surface level. Eleven km (7 mi.) of the north side elevated line were grade-separated (between Wilson Avenue, Chicago, and Central Street in Evanston) in the 1920s. The grade separation was developed by the Chicago, Milwaukee, and St. Paul Railroad at the behest of its tenant, the Northwestern Elevated Railroad (later, the Chicago Rapid Transit Company). The CTA eliminated some 7.3 km (4.5 mi.) of surface operations on the outer ends of the Garfield-Maywood-Westchester and Douglas lines in the 1950s. Completion of the Congress Expressway by 1960 made it possible to eliminate 4.0 km (2.5 mi.) of grade level operation with numerous grade crossings by relocating the rapid transit line into the expressway corridor.

FIGURE 5 Brooklyn Rapid Transit: street-running on New Utrecht Avenue at 63rd Street 1914 (from Edward B. Watson Collection, courtesy Arthur J. Lonto).

FIGURE 6 Chicago and Oak Park Elevated: temporary route on Randolph Street, 1902 (from collection of George Krambles, used with permission).

IMPLICATIONS

Street-running in mixed traffic, reserved lanes, or within median reservations introduces another, somewhat disparate element into an already complex traffic stream. It poses potential problems of reliability, safety, lower speeds, and reduced capacities, especially in downtown areas. For these reasons, many U.S. electric railways have made concerted efforts to get their operations out of the streets.

The preceding case studies indicate that electric railways eliminated street-running where this was possible and where resources were available. Many of these decisions were made when there was little auto use and competition, and when travel demand was growing.

Today, it is even more important to avoid (or minimize) street-running. There are more potential conflicts between autos and trains despite better traffic engineering. Moreover, there is a need to provide rapid and reliable transit service that is competitive with driving. Minimizing conflicts, accident potentials, and travel times is not possible where there is extensive street-running, especially in the city center and the area around it.

Street-running in the CBD and other congested areas, therefore, should be viewed mainly as the first stage of a future off-street, preferably grade-separated, system. The basic goal should be to plan for and provide off-street operations (even at-grade) as soon as possible. Incremental transitions to off-street operations should be achieved where time and cost constraints preclude grade-separated alignments initially. This suggests the "pre-Metro" incremental approach used in European cities such as Brussels and Frankfurt.

LRT systems such as Cleveland (Shaker Heights) and the new St. Louis LRT line provide good examples of how street-running can be minimized in the planning, design, and operation of new systems.

Obviously, there may be exceptions in which CBD street-running in reserved lanes or medians may be appropriate. These include: (*a*) low-frequency train service, (*b*) long block spacings, and (*c*) low auto traffic volumes. These, however, should be the exception rather than the rule. Operations in median reservations may be appropriate where the number of street crossings can be controlled and operating speeds of at least 25 mph can be maintained between passenger stops.

Vintage special-interest operations in pedestrian and transit malls are another exception. Low speeds and frequent stops are desirable to serve tourists, shopping, lunch time, or other short CBD trips.

Investments in rail transit can be substantial. They buy speed, reliability, safety, and capacity. These service improvements are best achieved in cities where the trains will not affect or be affected by, street traffic.

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REFERENCES

1. Korve, H., J. Farran, D. Monsel, and H. S. Levinson. Interim Report, TCRP A-5 *Integration of Light Rail Transit Into City Streets*, 1995.
2. Miller, J. A. *Fares Please*, Dover Publications, New York, N.Y. 1960.
3. Charles, Bradley H. Rapid Transit Boston. *Bulletin No. 9.* Boston Street Railway Association Inc., Cambridge, Mass., 1971.
4. Middletown, W. *The Time of the Trolley.* Kalmbach Publications, Milwaukee, Wis., 1967.
5. Boorse, J. W. *Philadelphia In Motion.* Bryn Mawr Press, Bryn Mawr, Pa., 1976.
6. *Transit—A Part of the Pittsburgh Plan.* Report No. 3. Citizens Committee on the City Plan of Pittsburgh, September 1923.
7. Shaughnessy, M. M. *Street Railway Requirements of San Francisco.* City and County of San Francisco, May, 1929.
8. *Rapid Transit for San Francisco.* Public Utilities Commission of San Francisco, 1936.
9. Landgraf, R. J. Pre-Metro Conversion, Now or Never. In *TRB, Special Report 182: Light Rail Transit: Planning and Technology*, TRB, National Research Council, Washington, D.C., 1978, pp. 62–67.
10. Molyneauv, D., and S. Sackman, ed., *75 Years—An Informal History of Shaker Heights.* Shaker Heights Public Library, 1987.
11. Drury, G. H. *The Historical Guide to North American Railways.* Kalmbach Books, Milwaukee, Wis., 1985.
12. Route of the Electroliners. *Bulletin 107.* Central Electric Railfans' Association, Chicago, Ill., 2nd ed., 1975.
13. Hilton, G. W., and J. F. Due,—The Electric Interurban Railways in America, Stanford University Press, Stanford, Calif., 1960.
14. Belt Lines of Illinois Traction System. *Electric Railway Journal*, Nov. 16, 1912.
15. Catherman, J. I. Belt Line Solves Freight Problem, *Electric Traction*, Chicago, Ill. Aug. 1927.
16. Middletown, W. *The Interurban Era.* Kalmbach Publishing Company, Milwaukee, Wis., 1961.
17. Crump, S. *Ride the Big Red Cars*, 3rd ed. Trans Anglo Books, Los Angeles, Calif., 1970.
18. California Railroad Commission. *Report on Engineering Survey of Pacific Electric Railway Company.* Los Angeles, Calif., 1939.
19. Wagner, C. M. The Washington, Baltimore and Annapolis Electric Railroad. *Bulletin 7: A Pictorial History of the Washington, Baltimore and Annapolis Electric Railroad.* Washington Electric Railway Historical Society, Inc. 1951.
20. *Chronological Order of Service Changes of Chicago Transit Authority and Predecessor Companies.* Chicago Transit Authority, September 1972.
21. Krambles, G. and A. H. Peterson. *CTA at 45.* George Krambles Transit Scholarship Fund: Oak Park, Ill., 1993.

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Diesel or Electric Power for Commuter Rail? It Depends . . .

MAURICE A. SULKIN

A study has been made for the North San Diego County Transit Development Board of the implementation of passenger rail service to an existing alignment that currently provides infrequent, low-speed, diesel-powered freight service over a 35.2-km (22-mi) right-of-way. At issue were the relative merits of the use of diesel-powered and electric-powered vehicles in providing superior service to a bus system currently in operation. Such performance analysis requires detailed definition of the alignment as well as the characteristics of potentially applicable vehicles. To provide the requisite data on the alignment, the physical characteristics were digitized, including curves, grades, tangent sections, and the location of station sites, in a form suitable for use as input to a computer simulation. A worldwide survey provided the requisite data on several diesel-powered and electric-powered passenger vehicles. Five potentially applicable vehicles (two diesel and three electric) were selected for the simulation process. Results of the simulation activity included speed and time versus distance profiles, energy utilization, and percentage of time at various throttle (power) settings. The simulation results showed that, on this specific alignment, there is little advantage to the use of electric-powered units over diesel-powered units. The reasons for this result were identified from the simulation data and are discussed in the body of this paper.

The North San Diego County Transit Development Board (NSDCTDB) was established by the California legislature in 1975 to plan, construct, and operate public transit systems in northern San Diego County. Its area of jurisdiction is 2 652 km^2 (1,020 mi^2) and includes the cities of Carlsbad, Del Mar, Encinitas, Escondido, Oceanside, Solano Beach, San Marcos, and Vista, as well as the Camp Pendleton Marine Base.

As part of its implementation plan, the Board has purchased the mainline right-of-way between Oceanside and San Diego and the branch line between Oceanside and Escondido, from the Atchison, Topeka and Santa Fe Railway Company. Passenger rail service on the San Diego mainline is currently being operated by Amtrak.

The NSDCTDB plans to implement commuter rail service between Oceanside and Escondido with an extension to the North County Fair Shopping Mall and an added loop to provide service to California State University, San Marcos (CSUSM). Use will be made of the existing Escondido Branch alignment. Currently, the line has a junction on its western end, with the Oceanside-San Diego mainline about 1.2 km (.75 mi) south of the Oceanside Transit Center Station, and terminates to the east in the vicinity of the Escondido Transit Center, a distance of slightly more than 35.2 km (22 mi).

Still to be resolved is the type of passenger vehicle best suited to the proposed operation. Self-propelled diesel-powered and electric-powered vehicles were considered. The electric vehicle offers better performance and lower noise and air pollution. However, it requires an overhead power distribution system not required by the diesel vehicles, and therefore, imposes more visual pollution and right-of-way (ROW) cost.

Electric-powered vehicles typically have higher power-to-weight ratios plus the ability to draw a large amount of additional power on a short-term basis, so they have superior performance characteristics when compared with diesel-powered vehicles. Although the advantage of electric-powered vehicles on straight and level track is clear, the performance on an actual alignment depends on the characteristics of that alignment, for example grades, curves, lengths of tangent track, and spacing of stations. Steep grades will adversely affect the diesel more than the electric vehicle. The superior acceleration of the electric will be of little advantage if curves are closely spaced, preventing the utilization of that acceleration because of curve speed limitations. Further, speed restrictions on an unsignaled alignment may further diminish the advantage of electric propulsion. On the other hand, the impact of the lesser acceleration capability and lower braking capability of the diesel may be exaggerated if there are many closely spaced stations so that the acceleration mode becomes a more predominant part of the operation. There are so many counteracting performance influences that performance comparison estimates on an alignment like that of the Escondido Branch can be competently made only through the use of a computer simulation incorporating not only the detail characteristics of the equipment but also the specific characteristics of the alignment.

The study described in this paper was initiated early in 1993 to provide insight and data to assist the Board in its decision-making process. This study incorporated the following process:

1. Define in detail the physical characteristics of the Escondido Branch alignment.
2. Survey the rail vehicle industry and obtain the characteristics of potentially applicable vehicles.
3. Select a small number of potentially most applicable vehicles, both diesel and electric.
4. Perform computer simulations using the combined alignment and vehicle characteristics as input to the RAILS simulation model.
5. Analyze and evaluate the simulator results and prepare findings.

This paper discusses each of the above steps in the process and presents a rationale for the somewhat unexpected results.

DESCRIPTION OF ALIGNMENTS

General Description

The planned alignment of the Oceanside-Escondido Line will include several new segments as follows:

Daniel, Mann, Johnson, and Mendenhall, 3250 Wilshire Boulevard, Los Angeles, Calif., 90010.

1. A new short section on the existing Oceanside-San Diego ROW between the Oceanside Transit Center Station and the Escondido Junction about 1.12 km (0.7 mi) south.

2. The existing alignment of the Escondido Branch from the Escondido Junction in a mainly easterly direction to the end of the line adjacent to the Escondido Transit Center and terminating in the vicinity of 4th Avenue between Redwood and Quince Streets in Escondido, a distance of about 34.1 km (21.3 mi).

3. A proposed extension from the current end-of-line, along an alignment in Pine Street, Center City Parkway, and Escondido Boulevard, to a terminal station in the parking lot of the North County Fair shopping center, a distance of about 6.4 km (4.0 mi).

4. A proposed CSUSM Loop segment, deviating from the Escondido Branch Line west of Valpredo Road, across SR78 and recrossing SR78 to rejoin the branch line just east of Woodland Parkway, a loop alignment length of about 2.72 km (1.7 mi).

Details of the alignment segments are shown on the Alignment Map, Figure 1.

Grades

Vertical profiles for all four segments are shown on Figure 2. (All grades in this report are stated as actual geometric grades and are not compensated for curvature. Ascending grades in the direction of increasing mileposts are designated as positive.)

The alignment transverses generally hilly country with little of the track bed on level ground. From an elevation of approximately 13.5 m (45 ft) at the Oceanside Transit Center Station site, the alignment descends to about 2.4 m (8 ft) at about milepost (MP) 0.6. It then rises steadily to an elevation of about 129 m (430 ft) east of Melrose Station site at about MP 7.8. From this peak, the alignment descends to an elevation of about 97.5 m (325 ft) near the Vista Transit Center Station site at about MP 9.3. It then rises to a new peak of about 156-m (520-ft) elevation at about MP 11.3. After descending again to an elevation of about 129 m (430 ft) at about MP 12.2, the alignment rises again, gradually, to its maximum elevation of about 207 m (690 ft) at the Nordahl Station site at MP 18.8. From this point, the elevation varies gradually to about 192 m (640 ft) at the end of the existing Escondido Branch at about MP 21.3. The proposed North County Fair Extension is relatively level to the Felicita Station at MP 22.5, then descends rapidly from an elevation of 198 m (660 ft) to an elevation of 114 m (380 ft) at the North County Fair station site at MP 25.3. This segment contains the steepest average and individual grades of the entire line. The average grade is −2.5 percent, and the maximum grade contained in the segment is −4 percent. Grades along the existing Escondido Branch and the planned North County Fair Extension vary from a few short segments of zero grade to many in the vicinity of 2 percent and one as high as 4 percent. The CSUSM Loop alignment

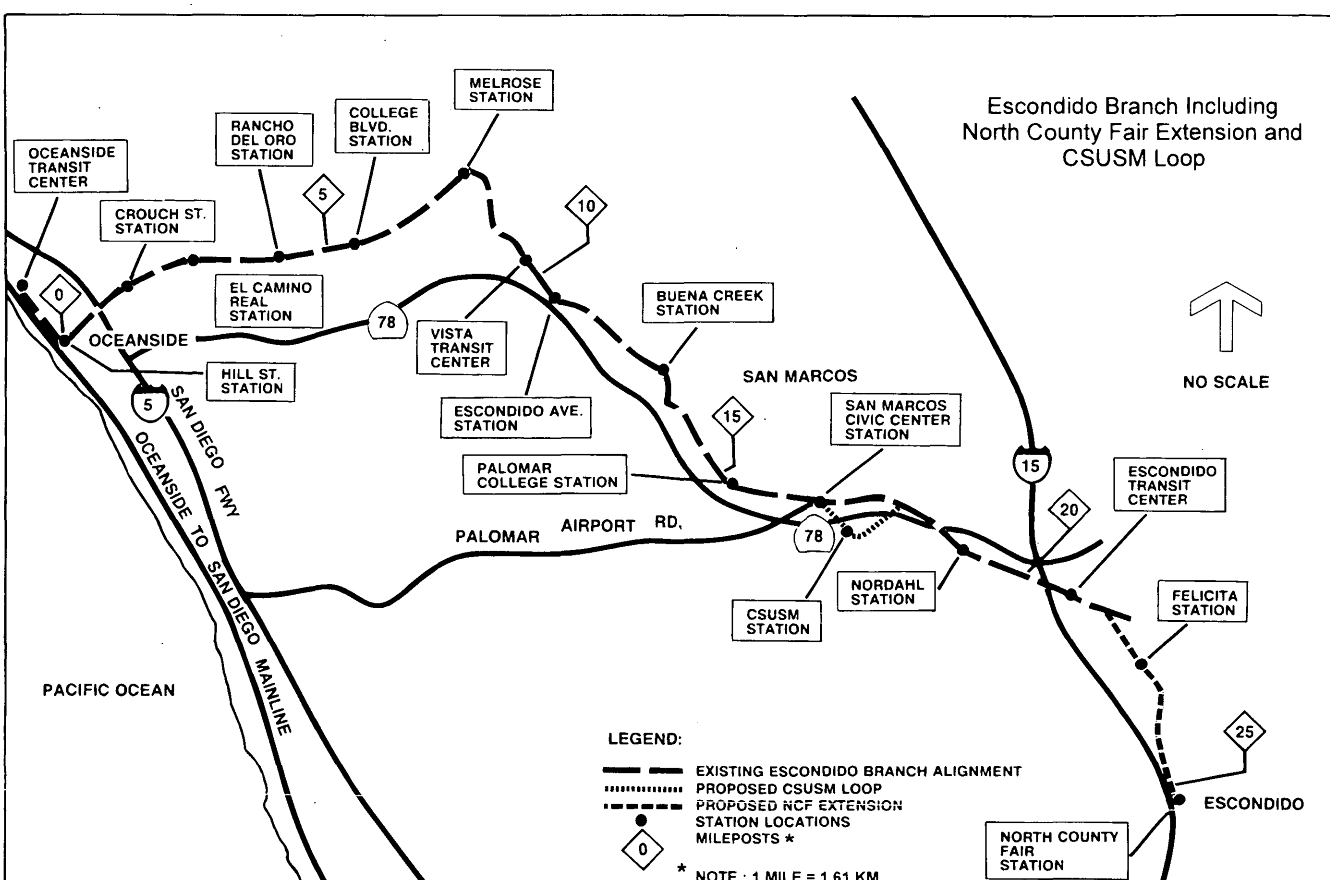

FIGURE 1 Alignment map.

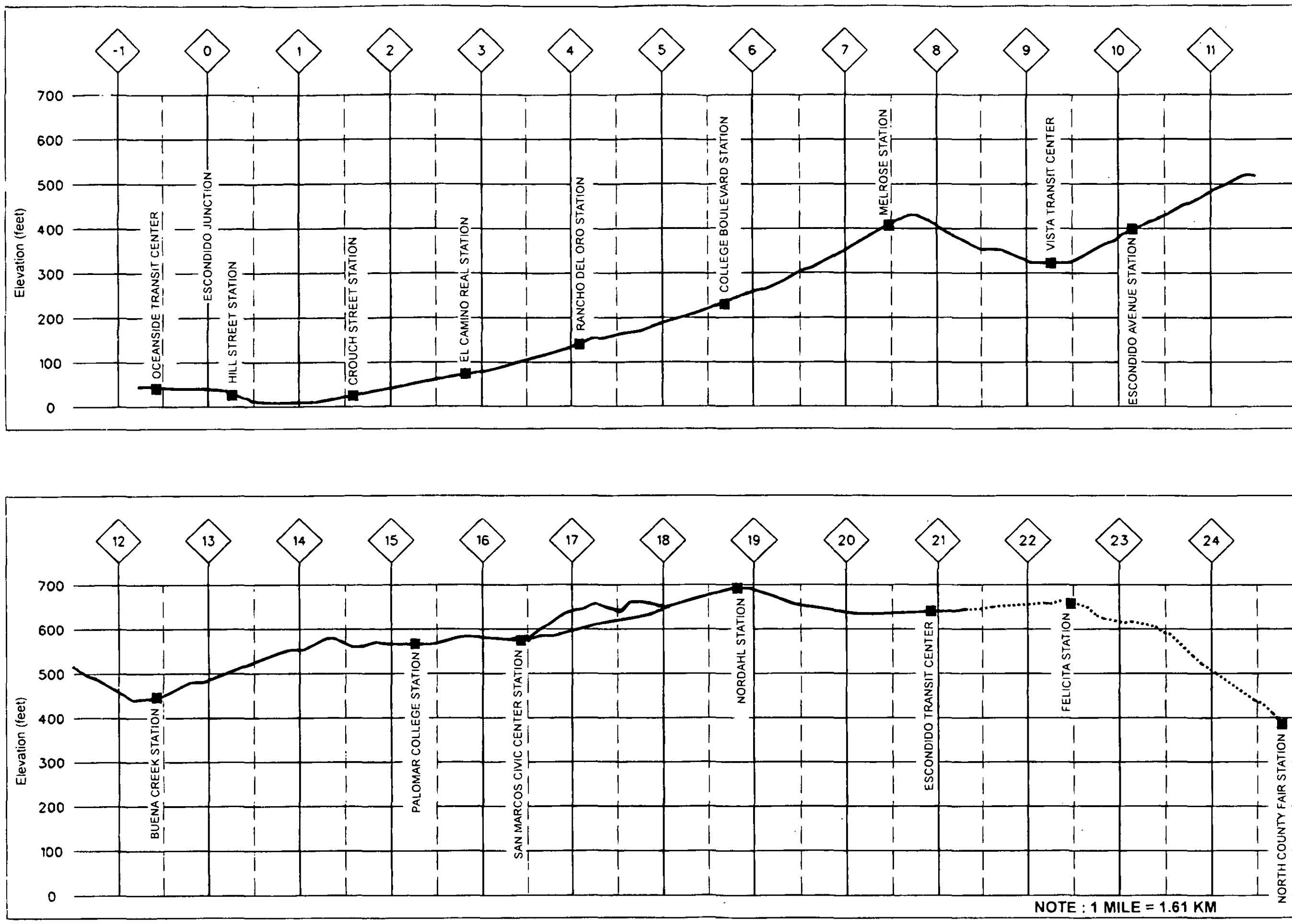

FIGURE 2 Alignment vertical profiles.

traverses similarly hilly country with grades reaching as high as 4.06 percent. Three new major bridges are included as well as a substantial amount of deep cutting into existing terrain. About 77 percent of the loop alignment is above existing grade.

Curves

The Escondido Branch alignment is characterized by many curves with few straight sections of any consequence between them. Over its approximately 33.6 km (21 mi) of length, there is one straight portion about 2.4 km (1.5 mi) long and two of about 1.2 km (0.75 mi) long. Others vary from about 0.8 km (.5 mi) in length to 0. There are 52 curves along the Escondido Branch varying from 1 degree to 10 degrees. There are several reverse curves with little or no intervening straight sections, limiting the use of superelevation. In a 1.6-km (1-mi) section of alignment, east of the Escondido Avenue Station site, there are eight curves of alternating direction of curvature with insignificant intervening straight sections.

The approximately 6.4 km (4 mi) of the planned North County Fair Extension contains 13 curves varying from about 3 degrees to about 27 degrees of curvature. It includes one straight section of about 2 km (1.25 mi). The 13 curves then occur in the remaining half of the alignment.

The approximately 1.12 km (0.7 mi) along the main line between the Oceanside Transit Center Station and Escondido Junction is all straight track. Two additional tracks and a passenger loading platform will be added in this segment of ROW to completely separate Escondido Branch operations from mainline operations. From the junction to the end-of-line of the Escondido Branch, 13 km (8.12 mi) of the 35.2-km (22-mi) length is taken up by curves. Thus, 38 percent of the branch line is occupied by curves. The planned North County Fair Extension has 1.7 km (1.06 mi) of curves in the 6.4-km (4-mi) length. This yields a combined curve length of 26 percent of the alignment length. The total line between Oceanside Transit Center Station and North County Fair Station, a distance of 41.6 km (26 mi), contains 14.7 km (9.18 mi) of curves occupying 37 percent of the length.

The CSUSM Loop alignment includes eight curves for an accumulated length of 1.3 km (0.8 mi) or a total of 47.3 percent of the length in curves. One major elevated curve changes the alignment direction approximately 90 degrees, from southward to eastward.

Stations

Including the new Oceanside Transit Center Station, the Oceanside-Escondido Line will have 14 stations, the North County Fair Exten-

sion, two stations, and the CSUSM Loop, one station, for a total of 17 stations system-wide at build-out. The alignment traverses a wide range of development characteristics, including dense urban residential and commercial areas, recreational, light residential and commercial, industrial, and agricultural. In other areas, the alignment is well sheltered from development of any kind.

Alignment Simulation Input

The detail physical characteristics of the alignment are an important input to the simulation process. For this purpose, the data from track charts, maps, and personal observation were assembled into tables of characteristics. Milepost designations for the beginning and end of each curve and change in grade, as well as the degree of curvature and the magnitude of the grade, were determined for all four alignment segments. Table 1 presents a sample of milepost positions of points-of-curvature (PC) and points-of-tangency (PT) as well as degree-of-curvature and direction for all curves. Positive values of curvature indicate curves to the right, and negative values, curves to the left. Also provided in Table 1 are the positions of stations.

MP 0 is located at Escondido Junction, so distances back along the mainline to the Oceanside Transit Center Station are designated by negative values. In addition, the distance along the CSUSM Loop between its junctions with the Escondido Branch is greater than the distance along the branch between these junctions (by about 0.64 km (0.4 mi)), so the MP along the loop have been identified by an *X*. The operating plan continues the freight operation on the branch alignment but is separated in time from the passenger trains, which will deviate from the branch and operate along the loop alignment. This has all been taken into account in developing the alignment data input to the computer simulation.

VEHICLE SURVEY AND DATA

Survey

A list of companies that manufacture vehicles potentially applicable to the planned Escondido Branch passenger rail service was compiled. Survey coverage was designed to include sources in the United States, Europe, and the Far East. The resulting list of potential sources contained 14 manufacturers. To assist in obtaining a complete and uniform set of responses, a data questionnaire was distributed, designed to provide general physical information on the equipment as well as the performance data necessary for input to the simulation studies.

Vehicle Data

Responses were received containing data on 14 vehicles, seven electric and seven diesel. The quantity and variety of responses is considered sufficient to allow selection of high state-of-the-art vehicles for the Escondido Branch study.

As a result of the survey, data was received on a range of equipment varying from small, light-weight, individual units with seating capacity for 45 passengers and seated weight of about 29,000 kg (64,000 lb) to multiple units with seating of about 180 passengers in a married pair weighing about 10 350 kg (230,000 lb) seated.

SELECTION FOR SIMULATION

A two-step selection process was used to reduce the number of vehicles to be subjected to the simulation process. In the first step, simpler, more obvious factors such as vehicle length and truck spacing were considered. These are important because the many curves and reverse-curves that exist on the Escondido Branch would introduce problems of clearance and passenger comfort with long vehicles and long truck spacing. Configurations with rigid lengths greater than about 2 250 cm (75 ft) were eliminated in the final stage of selection.

Seating capacity was normalized to a 2-2 configuration. Where an arrangement of 3-2 seating was submitted, the third row of seats was deleted from the vehicle capacity. For each seat so removed, the vehicle weight, empty, was reduced by 45 kg (100 lb). For vehicles where lounges and/or buffet areas were shown, it was assumed that seating would be provided in the same 2-2 pattern as for the remainder of the vehicle. The vehicle empty weight was not increased because seat weight was assumed offset by deleted buffet equipment weight. The increased number of passengers was included in vehicle loaded weight determinations.

TABLE 1 Track Characteristics

Limits	Curves		Grades %	Remarks
	Milepost*	Degrees		
PC	−0.78	−10°-0'	0.00	OCEANSIDE TRANSIT CENTER STATION BEGIN MAIN LINE
	−0.58			
	−0.38		−0.38	
	0.00		0.00	
PC	0.00	−6°-5'	0.00	BEGIN ESCONDIDO BRANCH
PT	0.02		−0.40	
PC	0.07	−5°-0'	−0.40	
PC	0.09	−10°-0'	−0.40	
PC	0.11	−3°-0'	−0.40	
PC	0.20	−8°-0'	−0.40	
	0.25		−0.40	HILL STREET STATION
PT	0.28		−1.60	
PC	0.30	−8°-0'	−1.60	
PT	0.35		−1.60	
	0.49	−8°-0'	−1.60	
	0.58		[illegible]	

* NOTE : 1 MILE = 1.61 KM

Vehicle capacity, per se, was not considered an important selection parameter at this stage of the analysis because system capacity can be adjusted to demand by selection of consist size and headway intervals. Vehicle general arrangement also was not considered a primary selection factor at this time. Factors such as seat arrangement, rest rooms, cab configuration, and boarding provisions can be modified to meet needs. An exception to the rule, however, is the requirement of a cab at both ends of the consist. For example, in the case of a power car with a cab at one end only, a consist of two power cars was required so that a cab would be available at either end. Where married pairs of motor and trailer cars were submitted, the trailer configuration with a cab at one end was selected for review for the same reason.

The inclusion of heating, ventilating, and air conditioning (HVAC) was mandatory. For diesel-powered vehicles, it was assumed that HVAC power would be provided from the main power source. The addition of HVAC was accompanied by a power reduction adjustment of 0.5 horsepower (hp) per seat for diesel units. No such adjustment was made for electric-powered units because HVAC power is normally not supplied from the traction power system.

For the second step of the selection process, the focus was on vehicle performance parameters. To aid selection, a Capacity-Performance Index, I, was developed as follows:

$$I = \left[\frac{N_s}{\mathrm{Aw}_0}\right]\left[\frac{\mathrm{hp}}{\mathrm{NA}}\right]$$

where

N_s = number of seats,
AW_o = empty weight,
hp = horsepower, and
NA = number of axles

I, then, is the product of the number of seats per pound of vehicle empty weight and the horsepower per vehicle axle. The value of I for each of the 14 vehicles is presented in Figure 3. These values, plus factors from the preliminary screening, were used to select for simulation the three electric- and two diesel-powered units as shown. These are *E-1*, *E-2*, and *E-3* and *D-3* and *D-4*.

SIMULATION INPUT

Assumptions

For the simulation software to provide realistic results, certain assumptions and limitations had to be identified consistent with the current and future status of the system. The resulting assumptions fall into three categories: ROW, traction power, and operations, as follows:

ROW Assumption

- The ROW consists of three segments: the first between the Oceanside Transit Center and the Escondido Junction, the second between the Escondido Junction and the Escondido Transit Center via the CSUSM Loop, and the third between the Escondido Transit Center and the North County Fair.
- Horizontal and vertical profiles are in accordance with the Description of Alignment (Section III).
- The existing line will be rehabilitated sufficiently to allow maximum speed limits for unsignaled territory.
- Curves will be superelevated to 3 in. where possible.
- No superelevation will be provided for curves closer than 150 m (500 ft).

Traction Power Assumptions

- Irrespective of power available, the application of power will be limited to not exceed acceptable levels of comfort (3 mphps).
- Electric motors have a short-term power rating of 1.7 times rated horsepower.
- Maximum tractive power (and braking) is limited to 18 percent weight on driving wheels.

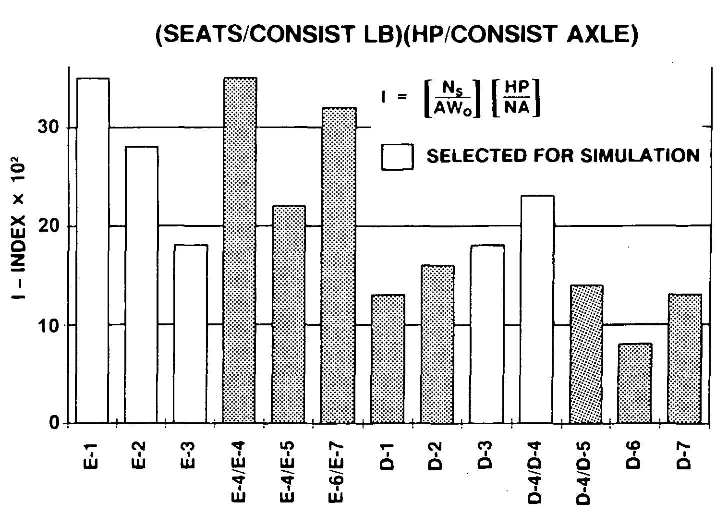

FIGURE 3 Capacity-performance index.

TABLE 2 Adjusted Consist Data

CON-SIST	NO. OF CARS IN CON-SIST	ADJ. NO. OF SEATS	ADJ. SEATED WEIGHT kg	NO. OF POWER AXLES	HORSEPOWER ADJ. TOTAL	HORSEPOWER PER kg WT. X10^3	HORSEPOWER PER SEAT	HORSEPOWER PER POWER AXLE X10^{-1}
E-1 E-1	2	154	82,387	8	1,504	18.26	9.76	18.80
E-2	1	60	40,088	4	812	20.26	13.53	20.30
E-3	1	64	41,260	4	742	18.00	11.60	18.57
D-3	1	80	50,678	4	500	9.90	6.25	12.50
D-4 D-4	2	160	94,323	4	1,220	12.93	7.62	30.50

- Adhesion was reduced by 0.002 times speed to allow for dynamic unloading and to reflect typical tractive effort curves for both diesel and electric units.

Operating Assumptions

- The maximum speed on the line is 72 km/hr (45 mph).
- Speeds on curves are allowed to impose 3 in of unbalanced superelevation.
- Speed limits are not increased for short tangent sections.
- Dwell time at all stations is 30 sec.

Vehicle Characteristics

Applying all of the ground rules, requirements, assumptions, and limitations, consist characteristics for the five selected vehicles were determined. These characteristics, as displayed in Table 2, were used as input to the simulation. Note that two of the vehicles, *E-1* and *D-4*, were of single-cab configuration, requiring a two-vehicle consist. Tractive effort curves for the five vehicles are presented in Figure 4.

SIMULATION RESULTS

Speed Limits

A considerable amount of attention was given to careful definition of the physical characteristics of the alignment and to development of realistic operating ground rules. This information allowed the simulation software to establish realistic speed limits throughout. The resulting speed limit profile is presented in Figure 5. Thus, an absolute speed boundary was imposed that limited all acceleration and braking activities along the alignment. These parameters were further controlled by the location of the passenger stations.

Speed/Time Profiles

The speed and time variations for a typical run between Oceanside and North County Fair are shown on a computer printout in Figure 6. A comparison with Figure 5 shows that the software closely controlled the actual speeds to not exceed the imposed speed limits.

The heavy diagonal line is the profile of time versus distance. The short vertical segments on this profile are the station dwell times. For this run, the eastbound trip time was about 55 min.

Trip Time

One-way trip times calculated by the simulator for the five selected vehicles are presented on the left-hand side of Table 3. For the

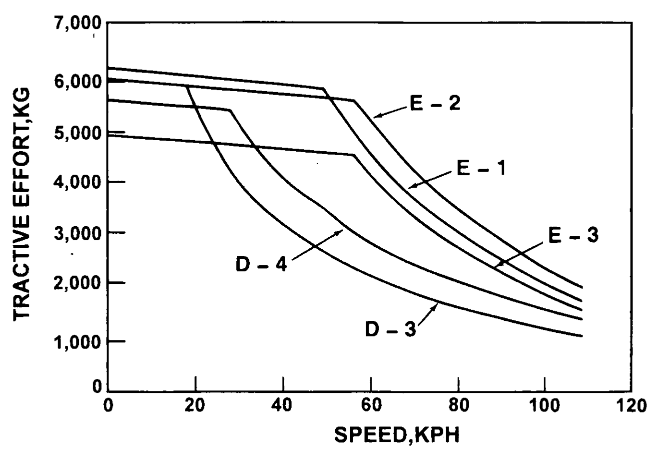

FIGURE 4 Tractive effort versus speed.

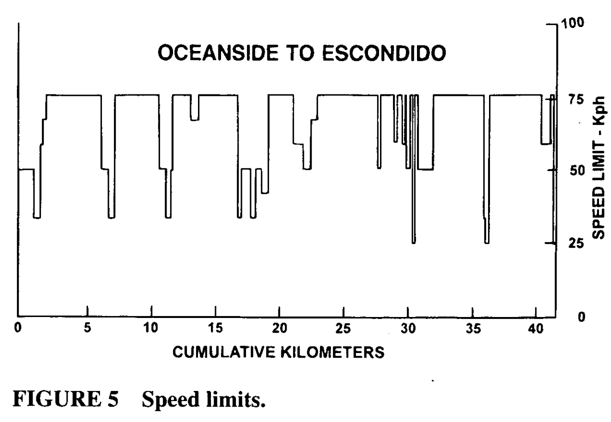

FIGURE 5 Speed limits.

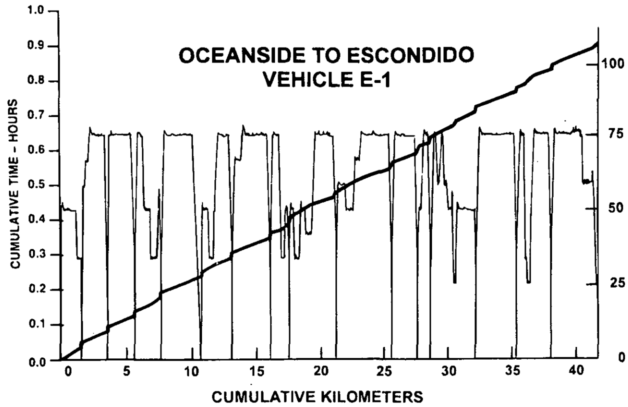

FIGURE 6 Time-speed-distance profiles.

established system speed limit of 45 mph, the times vary between 55 min and 57.6 min. The best time for an electric-powered vehicle is 54.8 min, and the best time for the fastest diesel-powered vehicle is 55.9 min, slower by about 1 min.

To test sensitivity of trip time to speed, runs were also made with a speed limit of 50 mph (Table 3). For the fastest vehicles, the trip times were reduced by 1 to 1.5 min. Note that this small improvement would require costly upgrading of the trackage and the addition of electrification and signaling systems.

Energy Consumption

The simulator also determined the quantities of energy consumed during a trip. These results are shown on the right-hand side of Table 3. Differences within a technology are minor. Of more significance is the energy cost per trip-seat. Such comparisons have been made and are presented in the following section.

Energy Cost Per Trip-Seat

The energy consumption data of Table 3 were converted to energy cost per trip-seat. For this purpose, costs of 10 cents per kilowatt-hour and 55 cents per gallon of diesel fuel were used. Seats-per-trip are based on the corrected seating values as provided in Table 2.

Results of the energy cost analysis are shown in Figure 7. Energy costs are presented for the electric-powered and diesel-powered vehicles as a function of the number of seats in the vehicle. Two trends are obvious. First, the diesel vehicles provide lower energy costs for a given vehicle seating capacity. Second, there is a significant trend of reduced energy-cost-per-trip-seat as the vehicle capacity increases. The difference in energy cost between the two technologies is reduced as vehicle capacity is increased. It appears that the difference would become negligible for very large vehicles of about 200 seats and above. For vehicles of about 75-seat capacity, the electrics provide a cost-per-trip-seat of about 41 cents compared with about 23 cents for the diesels. At a vehicle capacity of 150 seats, the electrics provide a cost of about 20 cents-per-trip-seat compared with about 13 cents for the diesels.

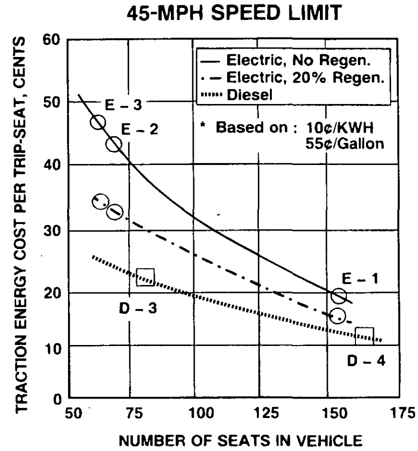

FIGURE 7 Trip-seat energy costs.

TABLE 3 Comparison of Energy Consumption

	ELAPSED TIME, MINUTES			ENERGY CONSUMPTION		
	75 KPH (45 MPH)	80 KPH (50 MPH)	DIFFERENCE	75 KPH (45 MPH)	80 KPH (50 MPH)	DIFFERENCE
E-1	55.06	53.32	-1.74	288.4 KWH	303.5 KWH	15.1 KWH
E-2	54.83	53.79	-1.04	288.3 KWH	308.5 KWH	20.2 KWH
E-3	56.07	54.62	-1.45	295.8 KWH	308.2 KWH	12.4 KWH
D-1	55.94	54.42	-1.52	139.6 L (36.9 GAL)	144.6 L (38.2 GAL)	4.9 L (1.3 GAL)
D-2	57.62	55.07	-2.55	127.2 L (33.6 GAL)	128.3 L (33.9 GAL)	1.1 L (0.3 GAL)

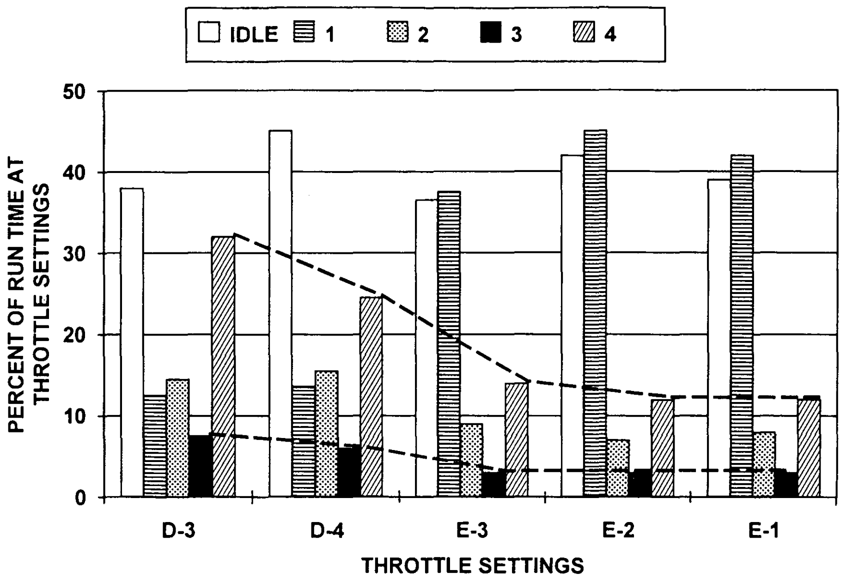

FIGURE 8 Traction power utilization.

To determine the potential impact on the energy cost comparison by regenerative braking, energy costs were determined assuming an optimistic value of 20 percent regeneration for the electric-powered vehicles. This regeneration capability was not sufficient to overcome the cost advantage of the diesel-powered technology. Further, it is unlikely that the commuter rail system under consideration would possess sufficient receptivity to provide any significant energy reduction from regeneration.

Traction Power Utilization

To better understand the trip time comparisons generated by the simulator, it was asked to provide percentages of trip time spent at various throttle settings. The diesel-power range was divided into idle plus four power settings. For comparison purposes, the continuous throttle setting spectrum of the electric-powered vehicles was divided into 20 settings in addition to the idle setting. Four groups of five of the throttle settings were established, each group of five being equivalent to one of the four diesel-powered settings above idle. In this manner, the relative times spend at each of the five throttle settings could be compared.

The power utilization simulation results are displayed in Figure 8, which contains groups of vertical bars for each of the selected vehicles. Each group of bars shows the percentage of trip time spent at each of the five throttle settings. It is immediately evident that both the electrics and the diesels are at the idle throttle position for more than 30 percent of the time.

For clarity, broken lines have been provided connecting the tops of the bars for the two highest throttle settings (three and four). The diesel-powered vehicles are at maximum setting for about 25 to 30 percent of the time, and the electric-powered vehicles required maximum throttle setting for only about 12 to 14 percent of the time. Similarly, for throttle setting three, the requirements were about 6 to 8 and 3 to 4 percent, respectively. It is obvious that the electric-powered vehicles possess far more power than is usable by the ROW limited performance of the Escondido Branch.

FINDINGS

This study has generated specific guidance for the implementation of passenger rail service on the Escondido Branch. It has also provided general guidance for planners engaged in the implementation process for any commuter rail service. These specific and general findings are as follows:

Specific Findings

There is no significant trip time advantage for the more highly powered electric vehicle for the following reasons:

- Because of alignment-specific performance limitations, advantage cannot be taken of the higher power of the electrics.
- Trip-seat fuel costs are lower for the diesel-powered vehicles.
- Because of the nature of the alignment, there is little to be gained by the expensive addition of electrification and signaling.
- There is potential for improved performance over that shown by more careful matching of the characteristics of the diesel units to the specific requirements of the Escondido Branch.

General Findings

- For other than alignments with ideal characteristics such as lengthy tangent sections, infrequent stations, signaling, and high-speed alignment geometrics, one cannot depend on the "conventional wisdom," and,
- For other than such ideal alignments, simulations should be used incorporating the detailed characteristics of both the vehicles and the alignment geometry.

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Generic Objectives for Evaluation of Intermodal Passenger Transfer Facilities

ALAN J. HOROWITZ AND NICK A. THOMPSON

A list of generic objectives is a tool for initiating the evaluation process for project alternatives for an intermodal passenger transfer facility. Such a list should contain all objectives that might be important to any project. This paper presents a list of 70 objectives developed through a literature review and through interviews with users. Each objective on the list was rated by a panel of experts on transportation planning and station design. An analysis of the ratings revealed that most important were objectives for ensuring safety and security and objectives for improving transfers and transfer opportunities. Less important were objectives relating to the environment and to finance. Architectural, building, and site considerations were rated as least important.

Like many other cities in the United States, Milwaukee has become concerned about the ability of its transportation system to continue to provide a high level of mobility while still attaining its environmental goals. To better meet these sometimes conflicting goals, public officials, planners, and citizens have started to place a greater emphasis on intermodal solutions to mobility problems. One effort in this direction is a study into the possible development of an intermodal station in Milwaukee's central business district.

Building an intermodal station in Milwaukee is both an opportunity and a challenge. The various transportation modes are widely dispersed throughout the downtown area, and historically there has been little effort toward coordinating functions or facilities. Further complicating the picture are yet unfinished plans to implement high speed rail service from Chicago and to build a light rail line and a busway from the western suburban communities. In such an ambiguous planning environment, planners need to explore a wide range of alternatives, exercising careful judgment, to find the best possible intermodal station. How should those judgments be made? There are no pat answers.

The last concerted effort to develop evaluation methods for intermodal stations in the U.S. dates to the 1970s. Since then issues, technologies, experiences, and priorities have shifted and evolved. Another look at intermodal evaluation seemed appropriate.

GENERIC OBJECTIVES

An evaluation framework needs a set of objectives, any one of which when met would foster the achievement of project goals. Objectives should be selected at the earliest point in the design process, but that selection is impeded by the size and complexity of an intermodal passenger transfer facility and by insufficient knowledge of project alternatives. There are many possible objectives. The selection of objectives would be helped by the availability of a rank-ordered list of generic objectives that span all potentially important design issues.

Lists of specific objectives are routinely created by planners when evaluating project alternatives. Some authors have developed lists of objectives or lists of design criteria as part of more general evaluation frameworks. Notable lists of station design criteria were written by a research team at the University of Virginia (*1*,*2*) and by Schneider (*3*). The Virginia list concentrated on interior design and site plans, and Schneider's list emphasized modal connections. Particularly interesting was a rank-ordered list of 10 objectives produced by Ross and Stein (*4*). This list was limited to the environment near a station, but it still illustrated the potential advantages for evaluation of ranked generic objectives.

RATIONALE FOR GENERIC OBJECTIVES

Many communities besides Milwaukee are seeking ways of improving their intermodal transfer facilities. The cost of these improvements can range from inexpensive to very expensive, and their impacts can range from minor to profound. It is essential that each facility be efficiently designed in a manner that satisfies the community's transportation needs and makes the best use of available resources. Critical to the design process is evaluation. The evaluation of a proposal for a new or improved intermodal transfer facility is a way to ensure that transportation objectives are met, that funds are well spent, and that the surrounding environment is protected and enhanced.

Evaluation requires judgment. An intermodal transfer facility is among the most complicated of transportation system components, often composed of hundreds of different design elements. An effective design must carefully balance these elements to achieve the best facility at a given cost. Hence, evaluation is not a single step but a process that starts with the design of alternatives and ends with a decision incorporating the opinions of experts, potential users, and the community at large. Designers must be cognizant of evaluation criteria, just as evaluators must be knowledgeable of the details of an alternative design.

At the inception of the design process, it is difficult to know what the community expects from the facility. Without plans and drawings and models to serve as a focus for early discussions, decision makers are unlikely to be able to give specific advice for selecting and refining the design elements. However, decision makers should be capable of expressing a set of general goals for the facility. A statement of goals, when available, is useful in defining the breadth of alternatives and in selecting a set of more specific objectives.

The final design of an intermodal passenger transfer facility has inputs from a variety of people, many of whom can influence the choice of alternative, including the choice of doing nothing. A

Center for Urban Transportation Studies, University of Wisconsin, Milwaukee, PO Box 784, Milwaukee, Wis. 53201.

successful facility will require the cooperation of public and private operators, governmental agencies, and community organizations. Many of these decision makers are business competitors; other decision makers compete for public funds or for private sector investment. They are of different sizes, have different missions, and have different constituencies. There are potential winners, and there are potential losers. Thus, it would be unreasonable to expect decision makers to provide a clear direction for the facility in the early stages of the design.

An intermodal passenger transfer facility is part of a very large system of transportation services. Its design requires it to be integrated with existing modes, perhaps making fundamental changes to the operation of those modes. It is necessary to involve the expertise of transportation planners and managers, as well as engineers and architects, in the design. Even broader expertise might be needed to mitigate adverse impacts on the physical environment and on society.

The evaluation of a large transportation project is often started after the alternatives have been completely defined and at least partially detailed. At that point each alternative is tested to determine how well it meets the project objectives. This procedure is reasonably good for projects with few objectives and for projects with few design elements. However, intermodal passenger transfer facilities can be very complex. Each alternative in itself may require numerous design decisions and tradeoffs. As indicated in Figure 1, each physical design must be influenced by the external environment, modal operators, financial needs, and travel requirements. This influence can only occur if the objectives are defined before the alternatives and if the staff interprets those objectives as it creates the design details (Figure 1).

There are many ways that an evaluation procedure may be implemented. However, a good evaluation procedure for an intermodal passenger transfer facility should have certain essential features. The evaluation procedure must:

- Be capable of generating and evaluating alternatives;
- Incorporate available expertise, including knowledge of modal operations;
- Foster the establishment of goals, objectives, and criteria for the project;
- Have sufficient staff support to accomplish necessary data collection, analyses, and reporting;
- Contain mechanisms for fast and clear communication among the many participants in the process;
- Satisfy the many laws and regulations associated with implementing a large transportation project; and
- Have the ability and authority to choose an alternative.

Furthermore, the process must be consistent with the style of planning that exists within the local community.

The design and evaluation process must have one or more groups of individuals with the responsibility to set project goals and to translate those goals into objectives. Each goal may have one or more objectives. An objective is a desired end-product of the project, but an objective is often operationalized as something the project should maximize, minimize, as well as achieve. There can be many objectives, and some objectives can be in direct conflict with each other. In defining objectives, it is especially helpful to look at those developed elsewhere. This paper presents generic objectives that cover the range of commonly established goals for intermodal passenger transfer facilities.

Ultimately, the evaluation process must determine whether some or all of the objectives have been satisfied. This determination may be aided by defining criteria for many of the objectives. Criteria are optional, quantitative measures of objectives.

BUILDING GENERIC OBJECTIVES

A list of generic objectives must be comprehensive without being specific to any particular alternative. Building such a list requires the opinions of many people familiar with the planning, design and operation of intermodal passenger transfer facilities.

As a first step, a comprehensive literature review of important objectives was performed. We sought every issue anyone has mentioned as being important to the evaluation of stations and terminals. The resulting list of issues was organized, and duplications were eliminated. At the same time, a review was conducted of evaluation methods that related to these issues.

To get users' opinions, an international, electronic group interview was conducted with knowledgeable and frequent users of intermodal passenger transfer facilities. The interview took about 1 month to complete. Administered through the Internet's "transit list," this group interview provided a good understanding of the issues most important to users. In addition, meetings were held with persons representing agencies and firms interested in intermodal station development in Milwaukee. They gave a sense for local concerns, expectations, and constraints.

The literature review and the interviews resulted in a long list of issues that at least one person thought was important. It was still necessary to determine whether some issues were more important than others. Consequently, a tight list of 70 generic objectives was developed, and planners from throughout the U.S. were asked to rate them. Individuals from the Internet's transit list and representatives from local agencies also gave ratings. The generic objectives

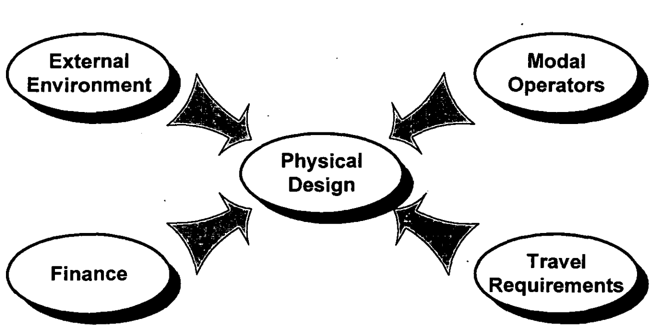

FIGURE 1 Factors affecting physical design.

Objective	Not Important										Extremely Important
Minimize Disorientation and Confusion	N	0	1	2	3	4	5	6	7	8	9	10

FIGURE 2 Example question.

spanned all categories of system planning, internal design, external design, and modal interfaces. Results are described later in this paper.

QUESTIONNAIRE DESIGN AND ADMINISTRATION

Questionnaire Design

The Generic Objectives Questionnaire organized the 70 objectives into four groups:

- System Objectives relating to the complete regional transportation system (*13*);
- Internal Objectives relating to the design of the facility and its site (*27*);
- External Objectives relating to the environment and the surrounding community beyond the site (*19*); and
- Mode Interface Objectives relating to aspects of the facility directly affecting transfers (*11*).

All objectives were rated on an 11-point category scale, as illustrated in Figure 2. A respondent had the capability of circling an "N" to indicate no opinion. Because of the possibility of confusing jargon, the respondents were provided with detailed descriptions of about half of the objectives. An attempt was made to reduce order bias by distributing two different forms with the questions reversed (Figure 2). A complete list of these objectives is found in Figures 3 and 4.

Selection of Expert Panel

The rating of a generic objective requires a person to work at two levels of abstraction. First, a panel member must be able to deal with a brief and technical description of a facility attribute. Second, a panel member must be able to relate the objective

OBJECTIVE CLASSIFICATION KEY

■	Transfer	⌘	Modal Enhancement
◆	Safety/Security	♣	Physical Environment
●	Access	♥	Nonphysical Environment
✱	Efficiency	□	Space/Site
★	Passenger	⊙	Architectural/Building
$	Financial	✪	Coordination

OBJECTIVE CATEGORY KEY

Mode Interface Objectives
Internal Objectives
System Objectives
External Objectives

Rank	Objective	Type	Rating
1	Maximize reliability of transfers.	■	9.0
2	Maximize security.	◆	8.8
3	Maximize safety and security of operations of modes.	◆	8.7
4	Minimize institutional barriers to transferring.	■	8.6
5	Maximize passenger information.	■	8.5
5	Achieve handicapped access.	●	8.5
7	Maximize safety.	◆	8.4
7	Maximize user benefits.	■	8.4
9	Maximize reliability of facility services.	✱	8.3
9	Maximize system legibility.	■	8.3
11	Maximize efficient access and egress.	●	8.2
11	Minimize disorientation and confusion.	■	8.2
11	Maximize coordination of transfer scheduling.	■	8.2
14	Minimize waiting.	✱	8.1
15	Minimize physical barriers of transferring between modes.	■	8.0
15	Minimize physical barriers to handicapped.	●	8.0
17	Minimize queuing delays.	✱	7.9
18	Minimize difficulty of ticketing or fare payment.	✱	7.8
18	Maximize ease of operations for modes.	✱	7.8
18	Maximize passenger comfort.	★	7.8
18	Maximize weather protection.	★	7.8
22	Maximize system coordination of information and fares.	■ ✪	7.6
23	Maximize directness of paths for modes.	✱	7.4
23	Maximize ease of fare collection.	✱	7.4
23	Maximize amount of connections between routes.	■	7.4
23	Minimize negative cultural impacts in surrounding neighborhood.	♥	7.4
27	Minimize path conflicts between modes.	●	7.3
27	Maximize directness of path.	✱	7.3
29	Achieve elimination of hazardous materials.	♣	7.2
29	Maximize quality of waiting areas.	★	7.2
31	Minimize costs.	$	7.1
31	Maximize joint development.	$	7.1

FIGURE 3 Composite ranking and scores of top-rated objectives.

OBJECTIVE CLASSIFICATION KEY

■	Transfer	⌘	Modal Enhancement
◆	Safety/Security	♣	Physical Environment
●	Access	♥	Nonphysical Environment
✱	Efficiency	◘	Space/Site
★	Passenger	⊙	Architectural/Building
$	Financial	✪	Coordination

OBJECTIVE CATEGORY KEY

Mode Interface Objectives
Internal Objectives
System Objectives
External Objectives

Rank	**Objective**	*Type*	*Rating*
33	Minimize barriers.	●	7.0
33	Minimize exertion.	★	7.0
33	Maximize market areas for each mode.	⌘	7.0
33	Maximize community pride.	♥	7.0
33	Minimize negative social impacts in surrounding neighborhood.	♥	7.0
33	Minimize physical impacts to surrounding neighborhood.	♣	7.0
33	Maximize flexibility for expansion.	◘	7.0
40	Minimize difficulty of baggage handling.	★	6.9
40	Maximize pedestrian assists.	✱	6.9
40	Minimize path length.	✱	6.9
40	Minimize crowding.	★	6.9
40	Achieve compliance with historic preservation requirements.	♣	6.9
45	Minimize conflicting paths.	✱	6.8
46	Minimize maintenance requirements.	⊙	6.7
46	Minimize service duplication.	✱	6.7
46	Achieve property rights.	◘	6.7
46	Achieve same or lower air pollution emissions.	♣	6.7
46	Minimize conflict with surrounding land uses, existing & proposed.	♣	6.7
51	Maximize aesthetics.	⊙	6.6
51	Maximize quality of architectural design.	⊙	6.6
53	Maximize amenities.	★	6.5
53	Maximize sense of place, historic significance, community image.	♥	6.5
55	Minimize regional air pollution emissions.	♣	6.4
56	Minimize construction impacts.	♣	6.3
56	Minimize disruptive land acquisition.	♥	6.3
58	Minimize level changes.	✱	6.1
59	Minimize fare inconsistencies.	$✪	6.0
60	Maximize urban renewal.	◘	5.9
61	Maximize reuse of existing buildings/infrastructure	◘	5.8
61	Maximize positive cultural and social elements.	♥	5.8
61	Maximize use of local employment.	♥	5.8
64	Maximize alternative uses of time while waiting.	★	5.7
64	Maximize openness of interior design.	⊙	5.7
66	Minimize regional energy consumption.	♣	5.6
67	Minimize wasted space.	⊙	5.5
67	Minimize negative impact on existing transportation services	$⌘	5.5
69	Maximize income from nontransport activities.	$	4.7
70	Maximize informal vending.	⊙	4.1

FIGURE 4 Composite ranking and scores of bottom-rated objectives.

to hypothetical alternatives. A rating will only be valid when a panel member is comfortable working with such abstract concepts. Thus, it would be unlikely that a typical user of a facility would be able to provide a meaningful rating. To overcome this limitation, we chose to recruit a panel of experts, recognizing that experts may not accurately represent the feelings of the population at large.

The expert panel selected to complete the Generic Objectives Questionnaire was composed of three subgroups. The first subgroup consisted of individuals from Metropolitan Planning Organizations (MPO), Regional Transit Authorities (RTA), and local governments who had been or were currently involved in an intermodal passenger transfer facility project. Several of the MPO and RTA had also been involved in intermodal facility projects. Attempts were made to incorporate panel members from regions and cities of all sizes and locations; however, no attempt was made to draw a random sample.

Agencies were contacted before distributing the questionnaires. At that point they were questioned about their willingness to participate and were asked for the name of the staff member most capable of responding to the questionnaire. A few agencies expressed reservations about their ability to answer the questionnaire because of a lack of prior involvement with intermodal facility projects. In these instances the agencies were not sent questionnaires. Agencies were contacted until a predetermined sample size of 50 was reached, of which 38 agencies returned questionnaires.

The second subgroup was composed of members of the Planning Advisory Group (PAG) from the Intermodal Station Feasibility Study for Milwaukee. Nine members of the group were sent questionnaires, and seven members returned questionnaires. The small sample was a result of both a small Planning Advisory Group and the fact that only one questionnaire was allowed from each agency. The Planning Advisory Group had many agencies represented by more than one individual. To avoid the chance that agency biases become reflected in the results, each agency was limited to one questionnaire.

The third subgroup consisted of members of the Transit List on the Internet (USR). Individuals in this discussion group are involved in the transportation field, either as consultants, transit agency personnel, professors, students, or hobbyists. The response rate from this group was only 7.3 percent, or 22 questionnaires. This

low response rate was expected because the questionnaire was not sent directly to individuals. Many members of the discussion group do not regularly participate and may have missed the questionnaire during the period that it was posted.

Although the panel members were asked to rate objectives on a scale of 0 to 10, most members rated the objectives fairly high. The average score of all objectives was 7.0. The above average ratings were expected because of the care taken to only include objectives that were determined to have importance to somebody. Furthermore, the panel members showed considerable enthusiasm for the subject.

Because the panel was not drawn randomly and because the panel was composed of people from throughout the United States, the ratings are not necessarily predictive of the importance of the objectives in any given metropolitan area. The ratings are provided only as a starting point for evaluation of local facility designs.

RATINGS OF GENERIC OBJECTIVES

Overall, the Mode Interface objectives were rated highest (average score of 7.98), with Internal objectives second (7.24), System objectives third (6.84), and External objectives scoring the lowest (6.45). This order was preserved among the panel subgroups, with the exception of the PAG, which ranked System Objectives (6.80) slightly higher than Internal objectives (6.74). Caution should be exercised, though, in gauging the significance of results from the PAG because of its small sample size.

No Mode Interface objective scored below 6.9, and no External objective scored above 7.4. Seventeen of the 20 highest rated objectives were Mode Interface or Internal objectives, whereas 15 of the 20 lowest rated objectives were System or External objectives. Figure 5 shows this generally high rating of the Mode Interface and Internal objectives compared with the System and External objectives.

Among the three subgroups, the Transportation Planning Agencies (TPA) panel members on average rated all objectives the highest, and the PAG generally rated all of the objectives the lowest. Only a few objectives differed substantially in rating from one subgroup to another. Table 1 lists these objectives and the rank they received within their category.

The results based on the original four objective categories (External, Internal, System, and Mode Interface) did not reveal many interesting patterns in the data. Consequently, the objectives were regrouped and reanalyzed based on facility attributes, services, or impacts. The objectives were regrouped under 12 new classes: Safety and Security, The Transfer, The Passenger, Access, Efficiency, Coordination, The Physical Environment, The Nonphysical Environment, Finance, Space and Site, Modal Enhancement, and Architecture and Building. A few objectives were placed into two classes. The questionnaire did not make reference to these particular classes.

Table 2 shows the average ratings of each class. Safety and Security objectives were rated highest with an average score of 8.63. Transfer objectives were rated second highest with an average score of 8.22. No other class rated above 8.0. It should be noted that the Transfer class had three times the number of objectives as the Safety and Security class, which tended to lower the Transfer's final rating. Transfer objectives accounted for three of the top five objectives, including the highest rated objective. Furthermore, 5 of the 10 highest rated objectives were from the Transfer class. Table 2 shows the minimal importance given to the Architecture and Building objectives. Of this class' five objectives, three were rated among the lowest six objectives, including the overall lowest rated objective.

The five highest rated classes (Safety and Security, The Transfer, The Passenger, Access, and Efficiency) contributed 27 of the 28 highest rated objectives and 30 of the 39 objectives with an average score of 7.0 or higher. The five lowest rated classes (Nonphysical Environment, Finance, Space and Site, Modal Enhancement, and

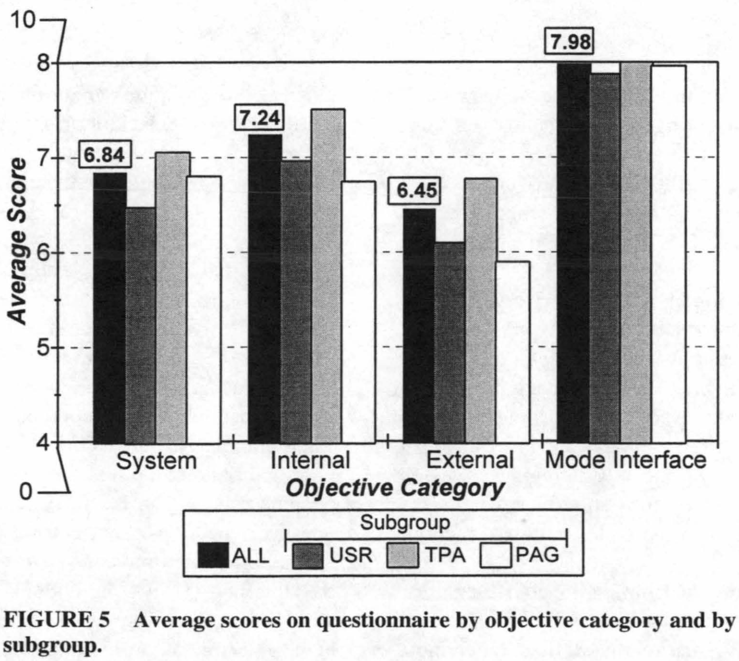

FIGURE 5 Average scores on questionnaire by objective category and by subgroup.

TABLE 1 Objectives Receiving Significantly Different Ratings Among Subgroups

		Rank in Category		
Category	Objective	TPA[a]	USR[b]	PAG[c]
EXTERNAL	Maximize use of local employment	17	18	1[d]
EXTERNAL	Minimize negative cultural impacts on surrounding neighborhood	2	12[d]	3
EXTERNAL	Achieve same or lower air pollution emissions	3[d]	12	16
EXTERNAL	Achieve compliance with historic preservation requirements	7	2	15[d]
INTERNAL	Maximize safety	3	4	17[d]
INTERNAL	Achieve handicapped access	1	10[d]	3
INTERNAL	Achieve elimination of hazardous materials	6[d]	26	26

[a]TPA: Transportation Planning Agency Subgroup
[b]USR: INTERNET Subgroup
[c]PAG: Planning Advisory Subgroup
[d]Subgroup that significantly varied from other subgroups.

Architecture and Building) accounted for 9 of the 11 objectives that received an average rating below 6.0.

The detailed results of the questionnaire are displayed in Figures 3 and 4.The ranking and scores reflect a compilation of all subgroups. Figures 3 and 4 list both the original category and the class of the objective, its ranking among all objectives and the average rating it received.

DISCUSSION OF RESULTS

The list of generic objectives covers only those issues that should be considered when choosing an alternative. Intentionally omitted are many objectives that relate to design details, operation, and maintenance.

An analysis of the ratings revealed that most important were objectives for assuring safety and security and objectives for improving transfers and transfer opportunities. The expert panel clearly stated that intermodal passenger transfer facilities should be evaluated primarily on how well they improve existing trip making. Everything else is of secondary importance. Architectural and building considerations, which are often the focus of station rehabilitation projects, were rated as being least important.

Many of the objectives are similar or functionally redundant. For example, the objective of maximizing user benefits fully encompasses the objective of minimizing waiting and partially covers many other objectives. Any given project could get by with a much smaller list of objectives by simply eliminating those objectives whose design elements are covered elsewhere.

To a large extent these results represent conventional wisdom among those involved in the planning and evaluation of intermodal passenger transfer facilities. Innovative or timely ideas tend to fare badly in these types of surveys. For example, informal vending (push carts and the like) has been strongly recommended by Beimborn and coauthors (*5*), but it was rated dead last by the experts in this panel.

TABLE 2 Objective Ratings by Classes

Objective Classes	Average Score	Number of Objectives
Safety/Security	8.63	3
The Transfer	8.22	10
Access	7.80	8
Efficiency	7.34	5
The Passenger	6.98	13
Coordination	6.80	2
Environment, Physical	6.60	8
Environment, Nonphysical	6.54	7
Space/Site	6.35	4
Modal Enhancement	6.25	2
Finance	6.08	5
Architecture/Building	5.87	6

CONCLUSIONS

A good evaluation of an intermodal passenger transfer facility is complicated; simple formulas do not exist. Of primary importance is the ability of a facility to improve trip making. Improvements in trip making can come from reductions in cost, in-vehicle time, out-of-vehicle time, physical and institutional barriers to transferring, and positive changes to the transfer environment.

Because of the large number of factors involved in intermodal transfer facility design, it is important that goals and objectives be articulated very early in the design process. However, decision makers may find it difficult to establish project objectives without reference to specific alternatives to be developed later. A list of generic objectives, like those presented in this paper, is helpful in arriving at a working set of project objectives before the formulation of any of the alternatives.

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REFERENCES

1. Demetsky, M., L. A. Hoel, and M. R. Virkier. *A Procedural Guide for the Design of Transit Stations and Terminals.* Report DOT-OS-50233. Program of University Research, U.S. Department of Transportation, 1977.
2. Hoel, L. and L. Richards, ed. *Planning and Development of Public Transportation Terminals.* Research and Special Programs Administration, U.S. Department of Transportation, 1981.
3. Schneider, J. B. *The Design of Intermodal Stations for a High Speed Ground Transportation System.* Federal Railroad Administration, U.S. Department of Transportation, 1994.
4. Ross, C. and J. M. Stein. Business and Residential Perceptions of a Proposed Rail Station: Implications for Transit Planning. *Transportation Quarterly,* Vol. 39, No. 4, October 1985, pp. 483–493.
5. Beimborn, E. A., H. Z. Rabinowitz, P. S. Lindquist, and D. M. Opper. *Market Based Transit Facility Design.* Report DOT-T-89-12. Urban Mass Transportation Administration, Office of Technical Assistance and Safety, University Research and Training Program, U.S. Department of Transportation, 1989.

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Airport Ground Access: Rail Transit Alternatives

SRINIVASA R. MANDALAPU AND WILLIAM J. SPROULE

Because of the increase in congestion in ground access at many airports, rail transit alternatives are getting increased attention. During the conceptual planning phase, it is useful to know the relative attractiveness of such alternatives over other modes. In this research, three concepts are examined: (*a*) an exclusive rail link from the city center, (*b*) an extension of an existing rail line to the airport, and (*c*) an automated people mover or shuttle bus connection linking the terminal area to a station on a nearby rail line. The concepts were evaluated using multicriteria analysis. Quantifiable criteria such as travel time and cost and nonquantifiable criteria such as accessibility, reliability, baggage convenience, and parking convenience were considered in the evaluation. Computer models were developed to determine quantifiable criteria values, and fuzzy ratings were used for nonquantifiable criteria. Passenger demands at which airport rail alternatives become attractive were identified for three usage levels of business passengers and vacationers. The effect of baggage-handling facilities at rail stations on service attractiveness is also presented.

Getting to the airport has become one of the biggest headaches for travelers today. Twenty years ago the solution would have been simply to add more highway lanes to the airport and provide more parking. However, many airports cannot utilize such options because of land resources and environmental concerns; as a result, rail transit options are being considered. Because of the large number of trips by air passengers, employees, and visitors to and from large airports, fixed-rail transit may have potential applications. The following sections summarize the research undertaken to study rail transit attributes and user characteristics. The information is then evaluated to assess the potential for airport fixed-rail service and determine what levels of demand are required for such service to be viable.

AIRPORT RAIL TRANSIT

Three basic categories of fixed-rail transit for airports were examined: conventional railway, urban rail rapid transit, and exclusive service (*1*).

Conventional Railway

The use of conventional intercity or commuter railway lines is common at several European airports. These access links consist of special-purpose spur lines that are connected to the existing rail network. As a result, conventional railway access can be relatively inexpensive because airport trains share lines with other rail services over much of the route. Conventional railway systems are usually oriented to a main station in the central city, and, although they will serve this destination very well, one must remember that in many cities most travelers do not have a city center destination.

Urban Rail Rapid Transit

Some airports have direct access to the metropolitan urban rail rapid transit system in the airport terminal. This type of access has several significant advantages. Usually, the rapid transit system is a coordinated part of the overall metropolitan transit system, giving air passengers and airport employees reasonable access to a large portion of the urban area. Because the rail rapid transit line operates on a reserved right-of-way, fairly reliable service is available.

In airports where rail rapid transit links have been built, these links have typically been short extensions to existing systems. The airport station is one stop on the network, and on many systems it is an end station on a line. Because most rapid transit systems are radial, airport lines tend to serve the central city best, and because trains must make frequent stops en route, high overall trip times are common. As with conventional railway systems, the greatest difficulty is the mixing of baggage-laden air passengers with other passengers, especially during peak periods. Typically, stations have not been designed for passengers with baggage and so travelers experience problems when stations are crowded.

Exclusive Service

One of the most significant technological advances to capture the public imagination in recent years has been the concept of a high-speed, nonstop train that transports passengers from the airport to the city center. Many such trains have been suggested and investigated all over the world but none have been built. The disadvantages of such a system are the high costs, and the fact that only a portion of the airport traffic will want to travel between the airport and the city center.

EXISTING AIRPORT RAIL SERVICES

Table 1 lists world airports that are directly served by a fixed-rail transit line in which a station has been incorporated in or near the passenger terminal. More information is available in the literature. (*1,2*).

In the United States, eight airports have airport rail service. At Atlanta Hartsfield, Chicago Midway, Chicago O'Hare, Cleveland Hopkins, and Washington National airports, the transit line is part of the metropolitan rail rapid transit network, which provides travelers with access to many destinations in the urban area. In

University of Alberta, Department of Civil Engineering, Edmonton, Alberta, T6G 2G7 Canada.

TABLE 1 Airports with Rail Transit Service

United States	
Atlanta Hartsfield	Philadelphia
Chicago Midway	St. Louis Lambert
Chicago O'Hare	South Bend, Indiana
Cleveland Hopkins	Washington National
Other World Airports	
Amsterdam Schipol	London Stansted
Barcelona	Mexico City
Berlin - Schonefeld	Munich 2
Birmingham, U.K.	Paris Charles de Gaulle
Brussels	Paris Orly
Dusseldorf	Rome - Fiumicino
Frankfurt - Main	Tokyo Haneda
Geneva Cointrin	Tokyo Narita
London Gatwick	Vienna
London Heathrow	Zurich

Philadelphia, the airport line is a commuter rail service that links the airport with Penn Center in downtown Philadelphia. In South Bend, Indiana, the Michiana Regional Transportation Center is a multimodal center serving air, rail, and bus. St. Louis Lambert International, the most recent airport station to be added to this list, was opened in 1994 on the St. Louis Metrolink light rail transit network. There are also several airports in the United States in which express or shuttle buses link the airport with the nearest rapid transit station.

The use of fixed-rail systems for airport access is more common in Europe, where intercity trains and commuter-type connections to a central city rail station are used. British Rail's service to London's Gatwick and Stansted airports, Frankfurt's S-Bahn service to the Frankfurt-Main Airport, or the Munich S-Bahn service to the new Munich airport are a few examples of this type of service. The Amsterdam (Schipol), Geneva (Cointrin), and Zurich airports are examples in which the airport is one station on an extensive intercity rail network. The airport link with the London Underground at London's Heathrow Airport is an excellent example of a well-planned access connection. The new Chek Lap Lok Airport in Hong Kong is planning a fixed-rail service as a vital link in its development.

EVALUATION

Evaluating airport access alternatives is quite complex because planners must consider several factors or criteria. Some criteria, such as travel time and cost, can be quantified; others, such as convenience, reliability, and environmental effects, are not as easily quantified.

For this research, a hierarchical analysis proposed by L. Thomas Saaty in the early 1980s (*3*) was used. Saaty developed this evaluation theory and technique while working on contingency planning problems for the U.S. Department of Defense in the 1970s. Since then, his approach has been used in resource allocation, planning of public and private projects, and construction management (*4*).

The first step in the analysis is to identify the criteria. The second step is to develop a pairwise comparison matrix and determine the criteria weights. The pairwise comparison is done by comparing each criterion with others and assigning fuzzy values. Saaty examined and tested various scales and adopted a scale of 1–9 to reflect the human cognitive process. For example, when Criterion A is compared with Criterion B, a value of 1 is assigned if both criteria are considered equally important. A value of 9 is assigned if A is absolutely more important than B.

The values of pairwise comparison are represented in a matrix form as shown in Matrix 1. This is a reciprocal matrix ($a_{ij} = 1/a_{ij}$) with a unit diagonal indicating that a criterion is equally important to the same criterion. The pairwise comparison matrices could be developed at an individual airport using market surveys of user preferences.

MATRIX 1 PAIRWISE COMPARISON OF CRITERIA

$$
\begin{array}{r|lllll|}
 & C_1 & C_2 & C_3 & \ldots\ldots & C_n \\
C_1 & 1 & b_{12} & b_{13} & \ldots. & b_{1n} \\
C_2 & 1/b_{12} & 1 & b_{23} & \ldots & b_{2n} \\
[\mathrm{PWC}] = C_3 & 1/b_{13} & 1/b_{23} & 1 & \ldots. & b_{3n} \\
. & \ldots & \ldots. & \ldots. & \ldots & . \\
C_n & 1/b_{1n} & 1/b_{2n} & 1/b_{3n} & & 1
\end{array}
$$

b_{ij} = the fuzzy value for importance of Criterion i when compared with Criterion j
C_i = Criterion i
n = number of criteria

The eigenvector (CW) corresponding to the largest eigenvalue of the matrix [PWC] represents the weights of criteria (W_i). The largest eigenvalue of a reciprocal matrix lies between the largest and the smallest row sums, and it is greater than or equal to the size of the matrix. For a consistent pairwise comparison matrix, the largest eigenvalue would be equal to the size of the matrix, other eigenvalues would be zero, and the sum of all the eigenvalues would be equal to the largest eigenvalue. Small perturbations of the entries in a positive reciprocal matrix imply small perturbations in the eigenvalues. The consistency of comparison can be checked by using a consistency index, which represents the average deviation of other eigenvalues from the sum of all the eigenvalues of a consistent case.

The third step is to evaluate alternatives with respect to each criterion. For nonquantifiable criteria, the procedure is similar to the pairwise comparison described previously. Each alternative is compared with all other alternatives with respect to the criterion in question, and fuzzy values are assigned. The eigenvector corresponding to the largest eigenvalue of this matrix would give the criterion values of alternatives with respect to the considered criteria. Similar values are determined for other criteria.

Because the basic idea of the pairwise comparison matrix is to obtain the weights to be used in a linear utility function, the approach is extended to quantifiable criteria. The criterion values are obtained for each alternative, and the matrix for comparison can be determined by normalizing the criterion values.

The fourth step is to aggregate the criteria values for all alternatives with respect to each criteria into one matrix, as presented in Matrix 2. Column 1 corresponds to the eigenvector of the pairwise comparison matrix with respect to Criterion 1, Column 2 for Criterion 2, and so on.

MATRIX 2 CRITERIA VALUES FOR ALTERNATIVES

		Criteria			
	Alternatives	C_1	C_2	....	C_n
	A	c_{a1}	c_{a2}	....	c_{an}
Criteria values	B	c_{b1}	c_{b2}	....	c_{bn}
[CV] =	C	c_{c1}	c_{c2}	....	c_{cn}
	D	c_{d1}	c_{d2}	......	c_{dn}

c_{ij} = Value of alternative i with respect to criterion j
C_i = Criterion i
A, B, C, D = alternatives

The final step is to multiply the matrix of criterion values [CV] by the criterion weights [CW] to get the final weights of alternatives. These final values reflect all the criteria in proportion to their importance and can be used to rank the alternatives. The values might be treated as attractiveness measured on a relative scale.

FIXED-RAIL CONCEPTS

Three basic rail system concepts were examined (S.R. Mandalapu, unpublished Ph.D. dissertation, 1994):

- Concept A—A dedicated or exclusive line between the airport and city center. The service would provide express nonstop service. The airport station would be located in the terminal.
- Concept B—An extension of an existing fixed-rail line to the airport. The airport station would be located in the terminal.
- Concept C—An airport station would be located on a rail line that passes the airport. A shuttle bus or automated people mover system (APM) would link this station with the airport terminal(s).

The concepts were compared with auto, bus, and taxi service using the Saaty hierarchical analysis technique (S.R. Mandalapu, unpublished Ph.D. dissertation, 1994). A range of distances, average daily demands, number of business and vacation travelers, and baggage-handling facilities were examined. The criteria considered for the analysis included travel time, cost, reliability, baggage convenience, accessibility, and parking. Travel times and costs for a single-user trip were calculated using computer models developed for rail and bus systems, automobiles, and taxis.

Because the relative attractiveness of an alternative depends on the criteria considered, weights were given to each criteria. It was also realized that the importance of a particular criterion for a business traveler would be different for a vacationer, and as a result, weights were varied with the level of usage of business passengers and vacationers. Three levels of usage were considered: (*a*) more business passengers (90 percent), for which time is more important than cost; (*b*) an equal number of business and vacation passengers, for which time is as important as cost; and (*c*) more vacationers (90 percent), for which cost is more important than time.

Evaluation of Concept A: Dedicated or Exclusive Airport Fixed-Rail Link

This concept is for airports that are proposing a new fixed-rail link between the airport and the city center. The competing modes were automobile, taxi, and bus, and the evaluation criteria included travel time, trip reliability, mode accessibility, cost, baggage convenience, and parking.

In each case of level of usage by business passengers and vacationers, the multicriteria analysis is performed for various route lengths of 10 to 50 km with an increment of 5 km, and a minimum demand required for the rail alternative to be attractive is identified. The results of the analysis, presented in Figure 1, indicate that if only vacationers use the airport, exclusive rail links would be attractive when the rail transit passenger demand exceeds 50,000 per day. Few airports have such activity.

Evaluation of Concept B: Extension of Existing Fixed-Rail Links to Airport

This concept is for airports that are proposing an extension of an existing fixed-rail line from its present location to the airport. Good station access and good service information are assumed. The competing modes considered in the research are the automobile, taxi,

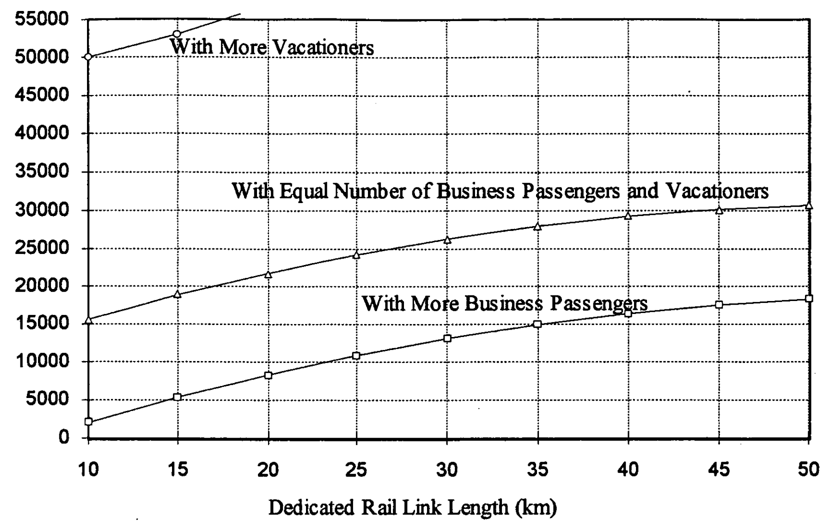

FIGURE 1 Variation of minimum passenger demand with route length for direct rail link (Concept A) to airports to be attractive for various demand levels.

and bus. The evaluation criteria included travel time, trip reliability, mode accessibility, cost, baggage convenience, and parking.

Multicriteria analysis was performed for total route lengths of 15, 20, 25, and 30 km. The extensions analyzed are from 2.5 km to 50 percent of the total route length with 2.5-km increments. For example, 2.5-, 5-, and 7.5-km extensions are examined for a 15-km route length. The cost of the trip on rail transit is determined by adding the actual cost per user on the extension and the fare on the existing line. Minimum demands required for the rail extension to be attractive were identified for each extension corresponding to each route length. The analysis showed that there is no considerable difference among the cases of same extensions of different route lengths; that is, a 2.5-km extension of 15-km total route length, a 2.5-km extension of 20-km route length, and so on. The averages of the results for the three cases are presented in Figure 2. The results suggest that if more vacationers use the airport, rail extensions beyond 10 km are not feasible for an airport. In such cases the system must attract more than 37,000 passengers per day.

Evaluation of Concept C: Rail Transit Station Near Airport with Shuttle Bus or APM System Connections

This concept may be applied to airports that use shuttle buses or an APM system to connect the airport terminal area to a station on a nearby rail line. The rail line may be an intercity or commuter rail line, or a rail rapid transit line.

The competing modes considered for evaluation of this fixed-rail concept are automobile, taxi, and express bus from the city center. These competing modes are compared with a rail service on the existing link with a shuttle bus service, or a rail service on the existing line with an APM link. Modal attraction is added to the previ-

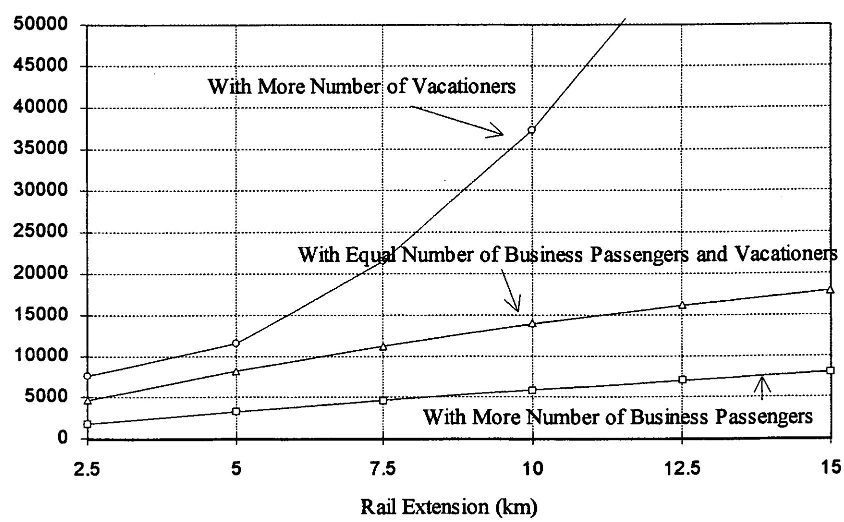

FIGURE 2 Minimum additional demand required for rail extensions to airport (Concept B) to be attractive for various passenger demand levels.

ous criteria: travel time, reliability, accessibility, cost, baggage convenience, and parking convenience.

Travel times for the rail plus shuttle bus and the rail plus APM alternatives are determined by adding the travel time on the existing rail link using the rail rapid transit model; the travel times on the connections are calculated using the shuttle bus model and the APM model. A transfer time from rail to the connection is added to the actual travel time.

The costs of trips by shuttle bus and APM are calculated using the respective models. The cost of a trip by APM system is calculated by assuming an elevated guideway. The total cost of a trip from the city center to the airport is calculated by adding the cost of a trip on the connection and the basic fare on the rail link. The evaluation of each case with the criteria was performed for total route lengths (including connections) of 15, 20, 25, and 30 km. The connecting lengths considered are 0.5, 1.0, 1.5, 2.0, 2.5, 5.0, 7.5, and 10.0 km. For example, for a route length of 20 km the combinations examined are 19.5 km of existing rail link plus a 0.5-km connection by shuttle bus or APM: 19.0 + 1.0, 18.5 + 1.5, 18.0 + 2.0, 17.5 + 2.5, 15.0 + 5.0, 12.5 + 7.5, and 10.0 + 10.0 km. The results indicated that there is no considerable difference between the route lengths for the same connecting length. The variation of minimum demand required for APM systems to be attractive for various route lengths for the three cases of preferences is presented in Figure 3.

INFLUENCE OF BAGGAGE CHECK-IN FACILITIES AT STATIONS

Baggage convenience is one of the key factors that influence the selection of airport access mode. Most vacationers have considerable baggage, whereas business travelers have few bags that are checked. If special baggage-handling facilities are provided, the influence on the modal attraction changes depending on the composition of passengers with the two basic journey purposes. To study the effects, baggage check-in facilities were examined for the concepts using the multicriteria analysis.

For the case in which baggage check-in facilities are provided at stations, the baggage can be checked in at the rail station(s), shipped to the airport, and loaded onto the respective airplanes. The responsibility for the baggage lies with the airline or the airline agent. There will be an additional cost involved for the airline to set up such facilities. Passengers must take the risk that their baggage may not travel with them on their flight. The penalty for baggage convenience on fixed-rail options is reduced to reflect the convenience of having the facility at stations. Even when check-in facilities are provided at stations, rail travel cannot be perceived to be better than automobile or taxi travel because of the risks mentioned earlier. Fuzzy criterion values were chosen to reflect the risks.

The analysis was carried out with a new set of criterion values for baggage convenience; the rest of the criteria are unchanged. The minimum daily passenger demands required for the fixed-rail alternative to be attractive are identified for various route lengths. The minimum passenger demands required for the fixed-rail options to be attractive for various route lengths with baggage check-in facilities at stations are presented in Figures 4–6.

CONCLUSIONS

In this study three concepts for rail transit access were developed and evaluated using multicriteria analysis. The criteria considered in the evaluation are travel time, trip reliability, mode accessibility, cost, baggage convenience, parking, and mode attraction. Passenger demand levels (required for rail alternatives to be more attractive than other conventional modes) were identified. The results are useful in the conceptual planning phase of fixed-rail links to airports from city centers.

The influence of travel time, trip cost, and baggage handling on the attractiveness of fixed-rail alternatives is considerable. The attractiveness of fixed-rail alternatives increases with an increase in demand. The attractiveness also varies with the number of business passengers and vacationers. The rail alternatives are attractive at lower passenger demand levels if more business passengers use the

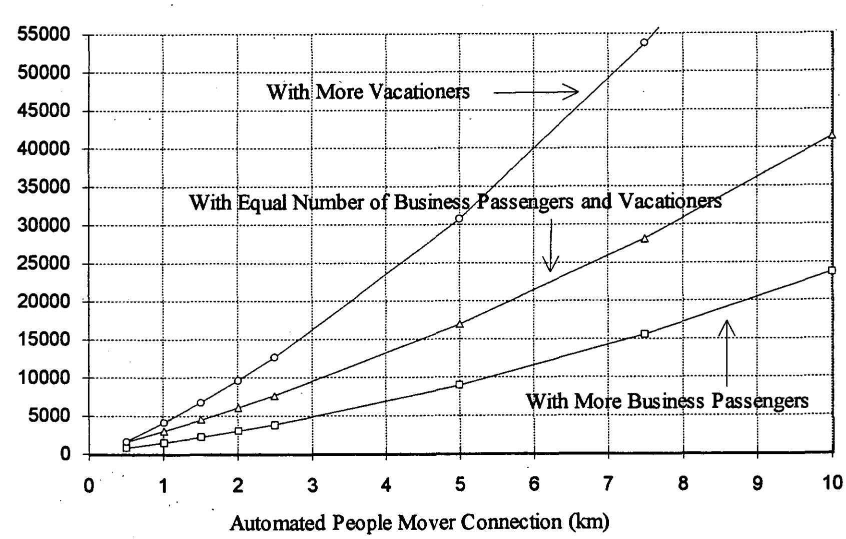

FIGURE 3 Minimum additional demand required for APM connection from rail station to airport (Concept C) to be attractive for various passenger demand levels.

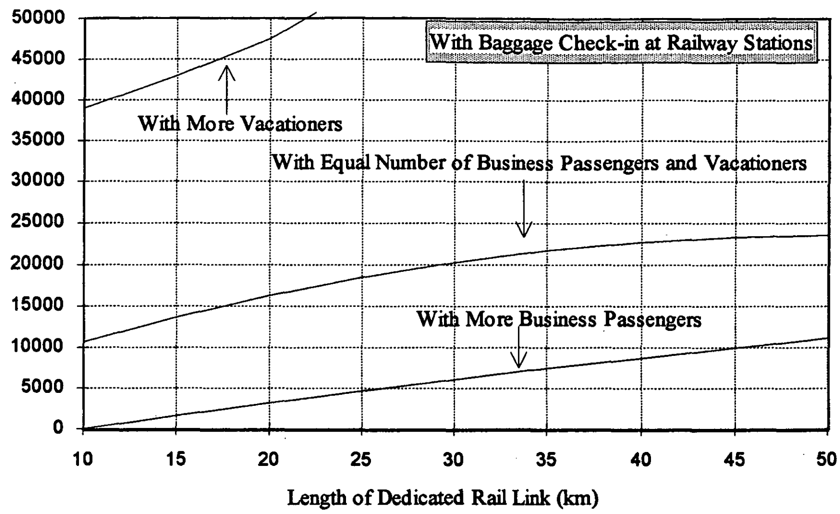

FIGURE 4 Minimum passenger demand required for the exclusive rail links to be attractive if baggage check-in facilities are provided at stations.

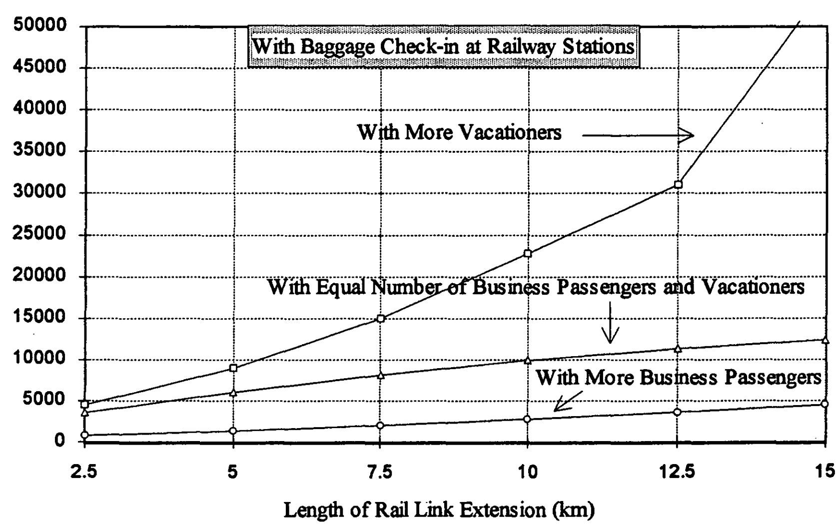

FIGURE 5 Minimum passenger demand required for the extension of rail links to airports to be attractive if baggage check-in facilities are provided at stations.

airport. Rail extensions are more attractive than exclusive links, and shuttle bus systems are more attractive than APM connections to nearby rail stations for short links and low demands.

The following conclusions may be made:

1. If an airport attracts a large number of vacationers, an exclusive rail link is not attractive until the demand is over 50,000 passengers per day.
2. If an airport attracts an equal number of business passengers and vacationers, exclusive rail links are attractive at demands over 15,000 passengers per day for a 10-km distance to over 30,000 passengers per day for a 50-km distance. For a rail extension to be attractive, the demand should be over 5,000 passengers for a 2.5-km extension to over 18,000 passengers per day for a 15-km extension.
3. If an airport is used by more business passengers, exclusive links are attractive at demands of over 2,500 to over 18,000 passengers per day, depending on the distance. Rail extensions are attractive when the demand is over 2,500 to over 7,500 passengers per day, depending on the extension length.

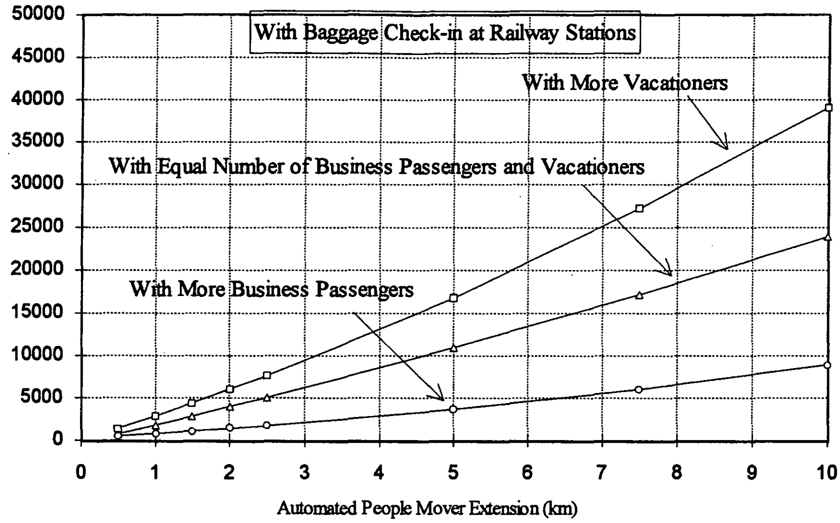

FIGURE 6 Minimum passenger demand required for the APM connection between airport and nearby rail station to be attractive if baggage check-in facilities are provided at stations.

4. Providing baggage check-in facilities at stations makes fixed-rail alternatives more attractive. The demand levels at which fixed-rail alternatives become attractive are 25 to 60 percent lower, depending on the rail concept and distance.

REFERENCES

1. Sproule, W. J., and S. Mandalapu. Opportunities for Fixed Rail Service to Airports. In *International Air Transportation—A New International Airport: Proc., 22nd Conference of the American Society of Civil Engineers,* Denver, Colo., 1992, pp. 223–231.
2. Mandle, P. B. Rail Service to Airports. In *Aviation Crossroads—Challenges in a Changing World: Proc., 23rd Conference of the American Society of Civil Engineers,* Arlington, Va., 1994, pp. 140–149.
3. Saaty, L. T. *The Analytic Hierarchy Process—Planning, Priority Setting, Resource Allocation.* McGraw-Hill, New York, 1980.
4. AbouRizk, S., S. Mandalapu, and M. Skibniewski. Analysis and Evaluation of Alternative Technologies in Construction Engineering. *Journal of Management in Engineering,* Vol. 10, No. 2, American Society of Civil Engineers, April/May 1994.

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Retrofit Techniques for Floating Slab Track

HOMER M. CHEN

The floating slab has been the primary method for mitigation of underground noise and vibrations in the Washington Metropolitan Area Transit Authority's (WMATA's) Metrorail system. Because of one type of defective polyurethane isolator pad supporting the floating slabs, about 18,800 track ft of floating slabs have settled unevenly, causing operation and maintenance problems. As an emergency measure, WMATA's maintenance forces raised the rails to the proper elevations by inserting shims under the rail fasteners on the floating slabs. There are about 80,000 ft (15 mi) of floating slabs in the WMATA operating system. About 22,400 ft (4.2 mi) are resting on this type of polyurethane pads, and 18,800 ft (3.5 mi) require new pads. Replacing pads under a floating slab segment 60 ton, 60 ft long, under restricted working conditions, presents a real challenge. The working hours are limited to nonrevenue hours between midnight and 5:00 a.m. Many techniques of repair have been developed and tried with the assistance of De Leuw, Cather and Company, WMATA's General Engineering Consultant. Two techniques have been successfully tried and are being used to lift the floating slabs for pad replacement. The retrofit has been performed by a Design Build team consisting of the Office of Engineering and Architecture and the maintenance forces from the Office of Track and Structure. For the circular tunnel sections, the technique is called window cutting with jacks and beams. For the box sections and passenger stations, the technique is called window cutting with jacks and stools. For the crossover and turnout areas, the technique has not been developed. It will probably be a variation of the window cutting with jacks and stools technique. As of December 1994, about 5,241 ft (1 mi) of floating slabs have been retrofitted by these two techniques with new natural rubber pads. To complete the retrofit, track alignment survey, noise and vibration measurements, and structural restoration are being performed after the pad replacement. The work is continuing wherever the trackright is available and may take the rest of the century to complete.

Floating slabs have been designed and installed in Washington Metrorail tunnels to reduce ground-borne vibration and noise transmitted to adjacent buildings. The concrete floating slabs rest on fiberglass, natural rubber, or polyurethane pads. Each pad is 6 in. in diameter or 6 in. square by 3 in. thick, spaced 2 ft on center. These pads serve as cushions to isolate structurally the floating slabs from the adjacent invert slabs (Figure 1).

There are two basic types of floating slabs, as shown on Figure 2. Type 1 is used in special trackwork (crossovers and turnouts) areas; Type 2, with two variations, is used in tunnel sections. The box section version of Type 2 has the contact rail sharing the same support with the running rail on the floating slab. The circular section version of Type 2 has the contact rail sitting on the adjacent invert slab.

The polyurethane pads furnished by one supplier were compressed unevenly (from 3 in. thick to as thin as ¼ in.) causing the slab to settle. The defective pads looked like squashed donuts. The worst ones disintegrated into piles of mud. Because the slab supports the track, this settling condition causes operation and maintenance problems including differential settlement, cross-level changes, contact rail height misalignment, uneven surfacing, corrugation, rail fastener breakdown, and train speed restriction. As an emergency measure, WMATA's maintenance forces from the Office of Rail Track and Structures raised the rails to the proper elevations by inserting shims under the rail fasteners on top of floating slabs (Figure 3).

Washington Metropolitan Area Transit Authority, 600 5th Street, N.W., Washington, D.C. 20001.

RETROFIT PROGRAM

There are 80,000 ft (15 mi) of floating slabs in the WMATA operating system. About 22,400 ft (4.2 mi) are resting on this type of polyurethane pads, and 18,800 ft (3.5 mi) require new pads.

Investigation Phase

Replacing pads under a 60-ton, 60-ft long floating slab segment under restricted working conditions is a challenge. Working hours are limited to nonrevenue hours between midnight and 5:00 a.m. Solutions had to be found before the replacement work could begin. De Leuw, Cather and Company (DCCO), WMATA's general engineering consultant, helped develop an investigation plan. It included

1. Problem Identification:
   –Review available criteria, specifications, shop drawings and test reports.
   –Conduct field survey to determine existing settlement and monitor future settlement.
   –Take noise and vibration measurements to determine whether the floating slabs are functioning as designed.
   –Test the defective pads to determine causes of the failure.
2. Analysis:
   –Develop criteria and specifications for procuring replacement pads.
   –Develop schemes for replacing the defective pads.
   –Develop procedures for demonstrations of the retrofit schemes.
3. Action Plan:
   –Perform equipment design and cost analysis.
   –Schedule on-site demonstrations of feasible retrofit schemes.
   –Evaluate and determine which schemes work implementation.

On the basis of a laboratory testing report prepared by the University of Akron, the defective pads were cured by the wrong method and the material compound consisted of polyester, which is much less resistant to hydrolysis than the polyether type of polyurethane for this application.

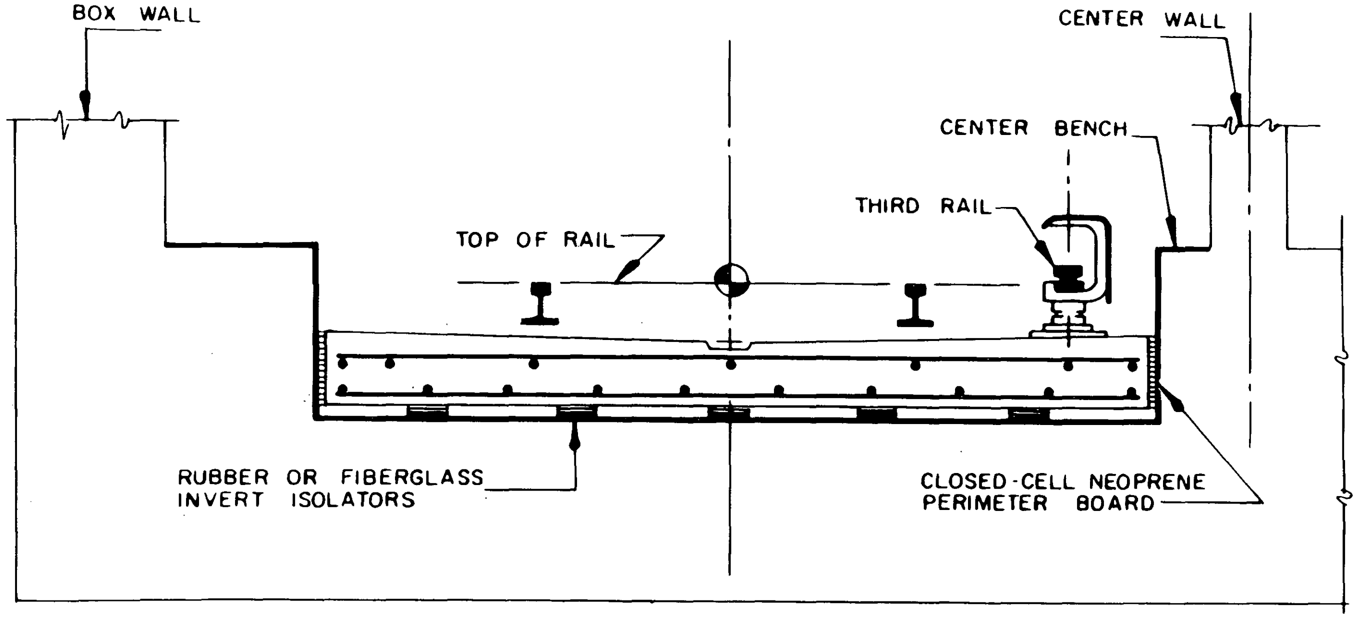


FIGURE 1 Typical floating slab section in subway box.

For the replacement pad design, 12-in. diameter by 3-in. thick natural rubber pads spaced 30 in. on center under the centerline of rail will be used for the Type 2 floating slabs, and 7½-in. diameter by 3-in. thick natural rubber pads bonded with steel plates on top and bottom, spaced 24 in. apart will be used for the Type 1 floating slabs. Natural rubber was chosen because it has better physical properties and creep characteristics (Figure 4).

Noise and vibration measurements conducted by Wilson, Ihrig & Associates, Inc., Acoustical Consultant, indicated the performance of the floating slab varied from one problem area to the next. With this information, it was determined how much of the attenuation should be restored in each area (Figure 5).

Implementation Phase

Replacement of the defective pads had been studied extensively. Many techniques were developed jointly by WMATA and DCCO, and three are workable under the restricted operating conditions. They are discussed in the following sections.

Window Cutting With Jacks And Beams

Figure 6 shows the general concept of this technique. It applies to the circular tunnel section with 7 ft 6 in.-wide floating slabs. The

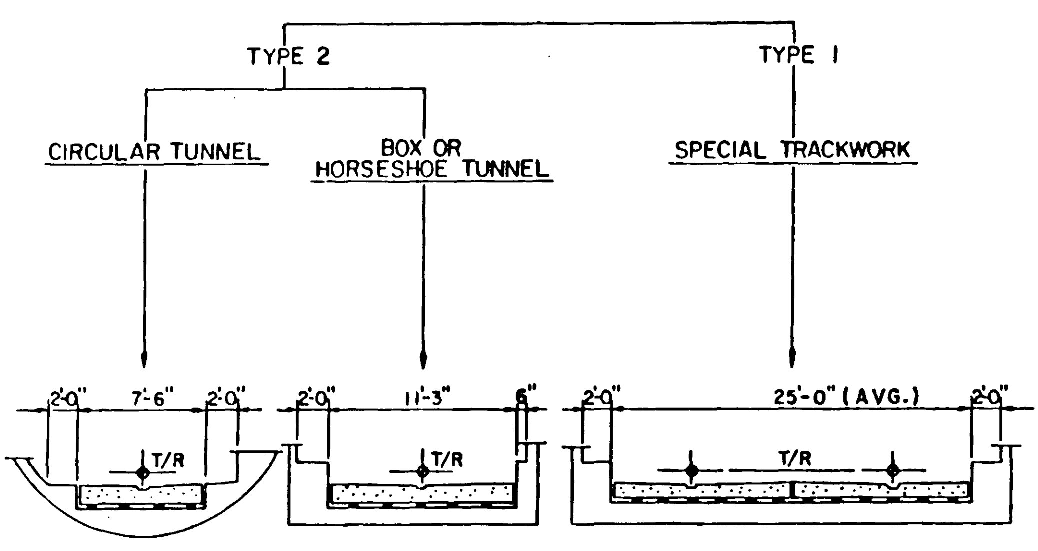


FIGURE 2 WMATA existing floating slab configurations.

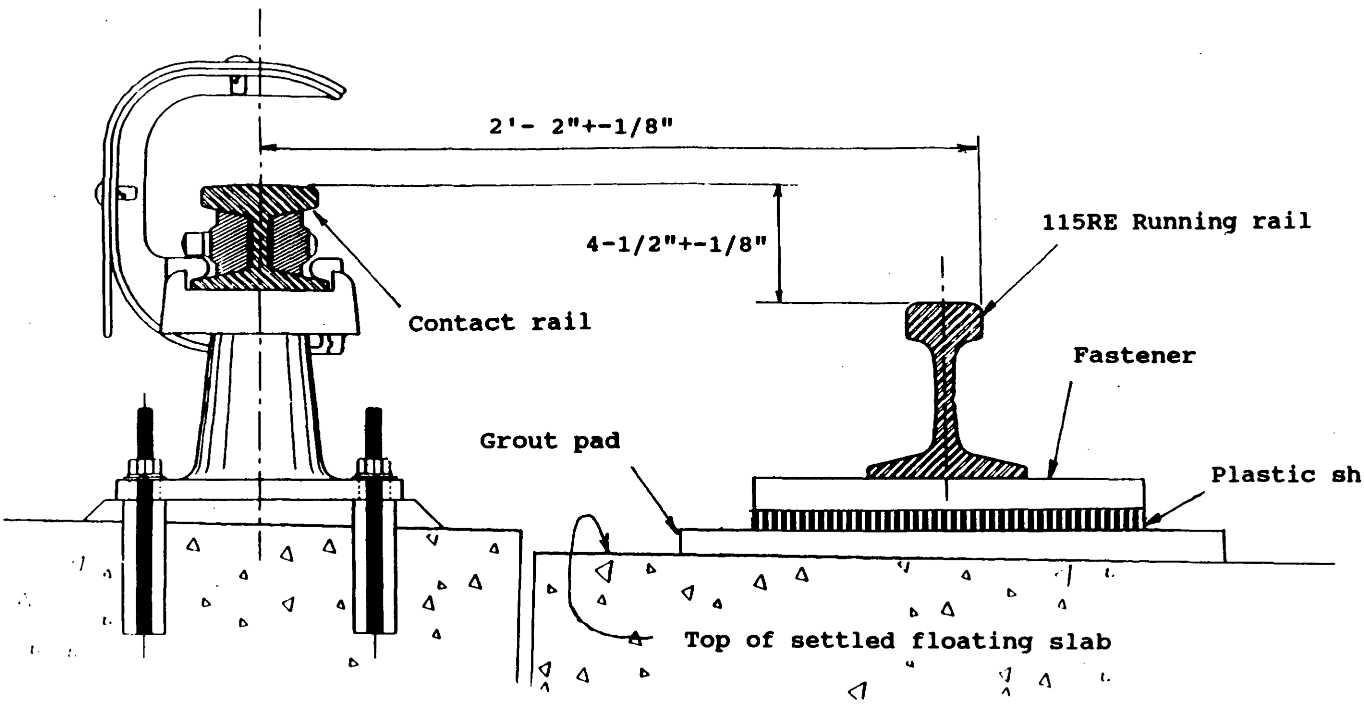


FIGURE 3 Settled floating slab with shim.

procedure is to core 16-in. diameter holes, 4 ft apart, through the 14-in. thick concrete slab, including the ⅛-in. metal pan used to support the slab during construction, along the centerline of the track. These openings are used for access to remove the defective pads and to install the new natural rubber pads. This coring can be done in advance without disturbing the existing track. Each hole takes about 50 min to make. Figure 7 shows the sections before and after the lifting operation. The jacking unit consists of a steel beam, two jacks with four hangers, and four rail fastener clamps. A synchronized jacking system (control box) is used to control the lifting operation. The steps are

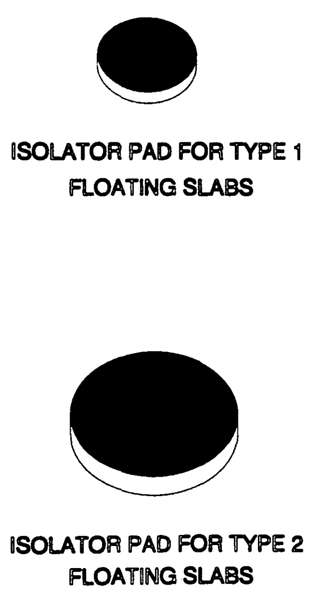


FIGURE 4 Replacement pads.

1. Preparatory Work:
   –Perform structural analysis for the lifting system.
   –Procure 50-ton hydraulic jacks, steel beams, hangers, straps, synchronized control box, and other hardware.
   –Procure new pads.
   –Core 16-in. diameter holes 4 ft apart along centerline of track.
   –Coordinate with Operations Central Control for work schedule.
   –Transport material and equipment, in advance, to the end of the station platform or fan vent shaft adit near the job site.
2. Retrofit Operation:
   –Turn off electric power on contact rail.
   –Secure work area.
   –Set up the lifting equipment.
   –Loosen the rail clips about 50 ft beyond each end of the floating slab segment to be lifted.
   –Lift the floating slab 4 to 6 in.
   –Insert 9-in. long square steel tube between the 16-in. holes to provide additional slab support in case of jack failure.
   –Remove defective pads from under the slab along the centerline of each rail.
   –Place new pads at 30-in. spacing under the centerline of each rail beneath the slab.
   –Lower the floating slab on the new pads.
   –Adjust both running rails and contact rail.
   –Provide rail transition tapering on each end of raised floating slab.

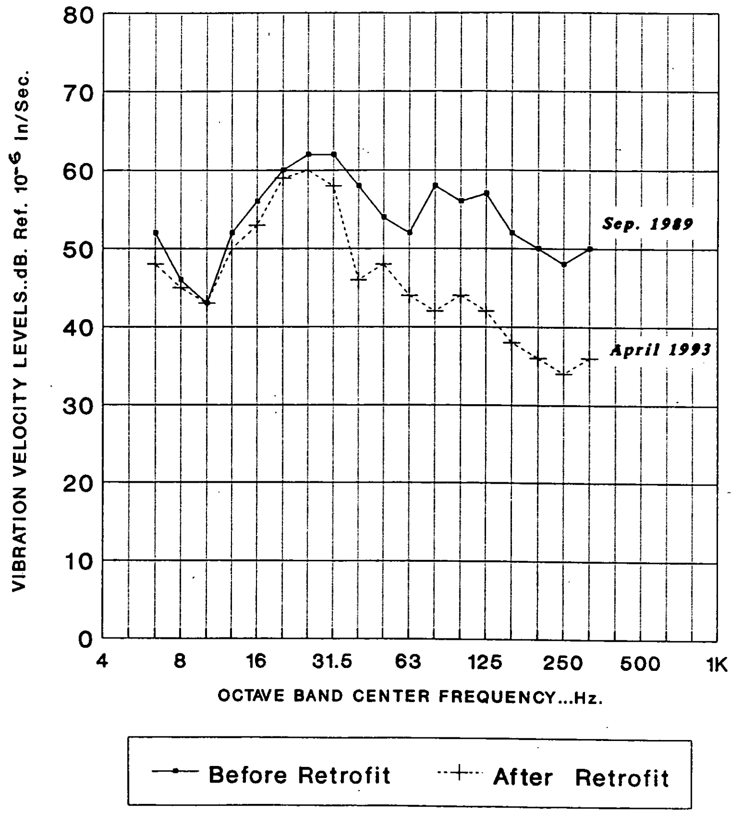


FIGURE 5 **Vibration measurements before and after retrofit (at Capitol South Station on tunnel safety walk 100 ft from platform).**

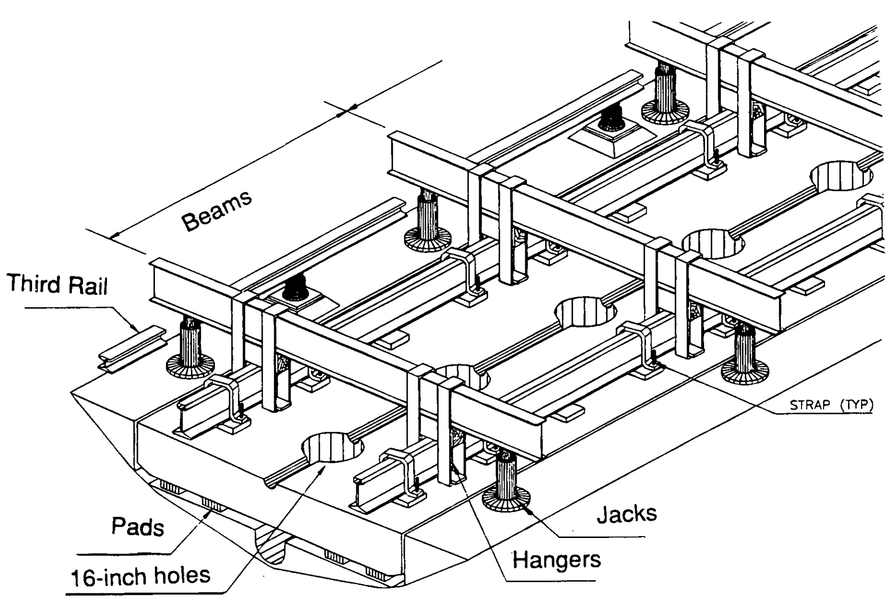


FIGURE 6 **Details of jacks and beams technique.**

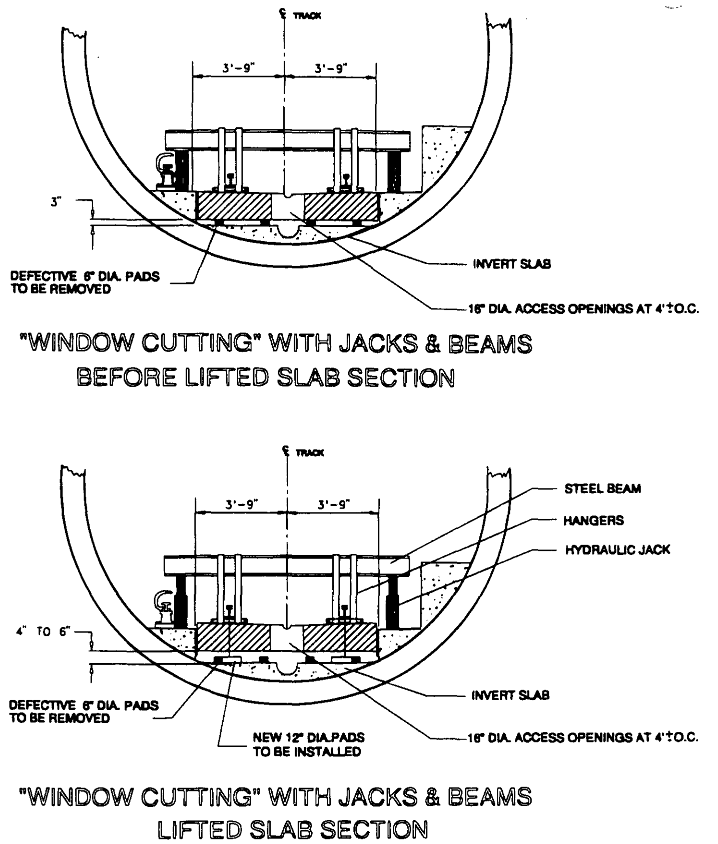


FIGURE 7 Sections before and after retrofit.

–Tighten rail clips.

–Replace concrete cores in the 16-in. holes with temporary 3-in. thick wooden block support.

–Run test train with speed restriction.

3. Restoration Work:

–Conduct field survey to determine as-retrofitted track conditions.

–Adjust rail profile and alignment.

–Conduct noise and vibration measurements to determine how much the attenuation has been restored.

–Remove concrete cores from the 16-in. holes and cover the holes with gray iron grates.

–Inspect floating slab and repair as required.

–Replace perimeter board at each side of floating slab.

Window Cutting With Jacks And Stools

Figure 8 shows the general concept of this technique. It applies to the slabs 11 ft 3 in. wide in the box sections, stations, and fan vent shaft sections where there is no room for jacks and beams. The procedure is the same as the window cutting with jacks and beams technique except for the lifting equipment. In addition, 5-in. diameter holes spaced 9 ft apart along the field side of the rails are cored while the 16-in. diameter holes are being cored. These 5-in. diameter holes permit the specially designed jacking unit to sit on the stand with stool-like equipment to lift the slab against the invert slab below. The stools are anchored to the top of slab around the 5-in. holes with four ⅞-in. anchor bolts. Figure 9 illustrates the layout of the system, and Figure 10 shows the sections before and after the lifting operation.

Variation of Jacks And Stools

This technique applies to special trackwork area. It is a variation of the jacks and stools technique and is still in the development stage. Briefly, the 16-in. diameter access holes and the 5-in. jacking stool holes are strategically located on the variable shape of floating slabs between the rails for the lifting operation. A demonstration of this technique is scheduled in fall 1995.

Progress Status

As of December 1994, about 5,241 linear ft of floating slabs were lifted for pad replacement. Because of restricted working hours, the estimated annual production rate is about 2,400 ft of floating slabs. In early retrofit operation, the time available to lift the floating slabs was limited to weekend after-midnight hours only. The improved skills and equipment, with single-track operation allowed at some locations, make it possible to retrofit on week nights. In fact, week

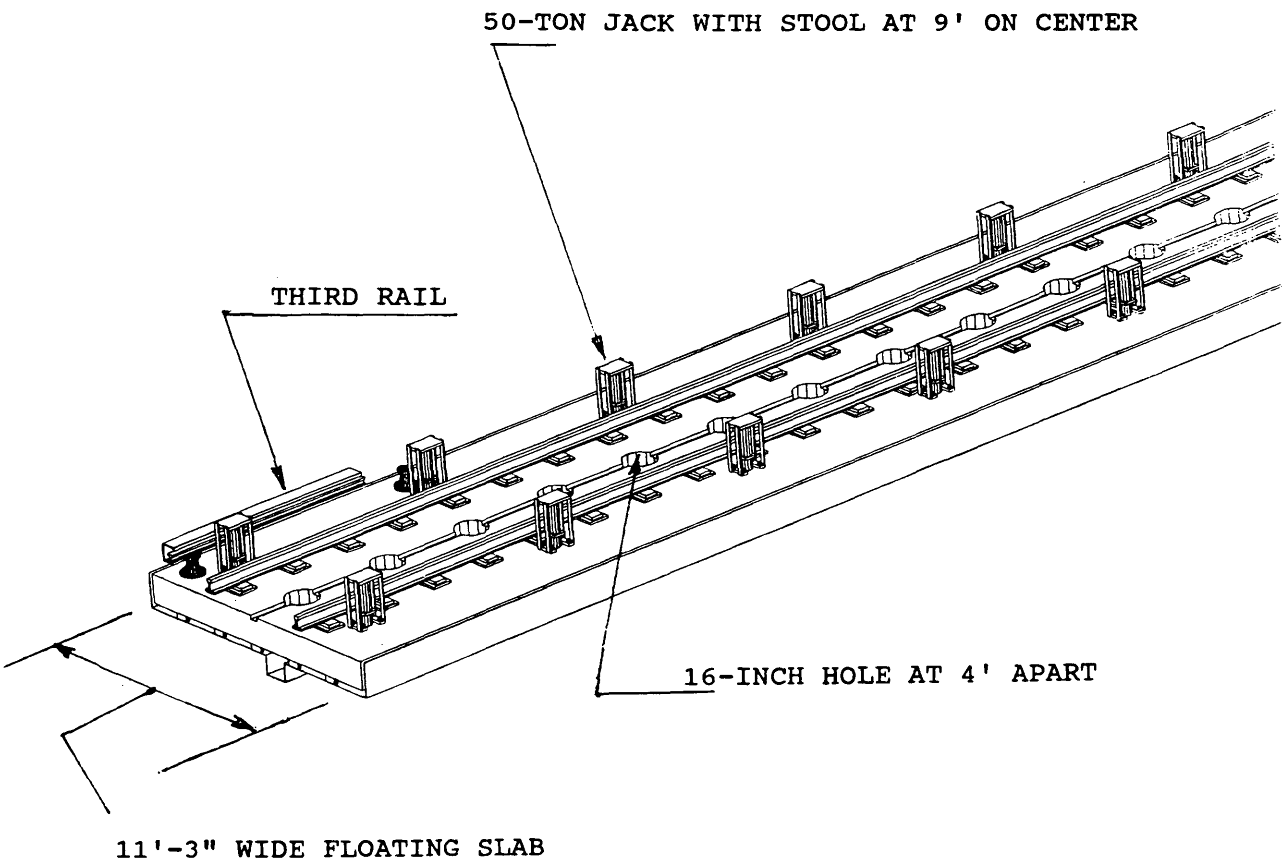


FIGURE 8 Window cutting technique with jacks and stools.

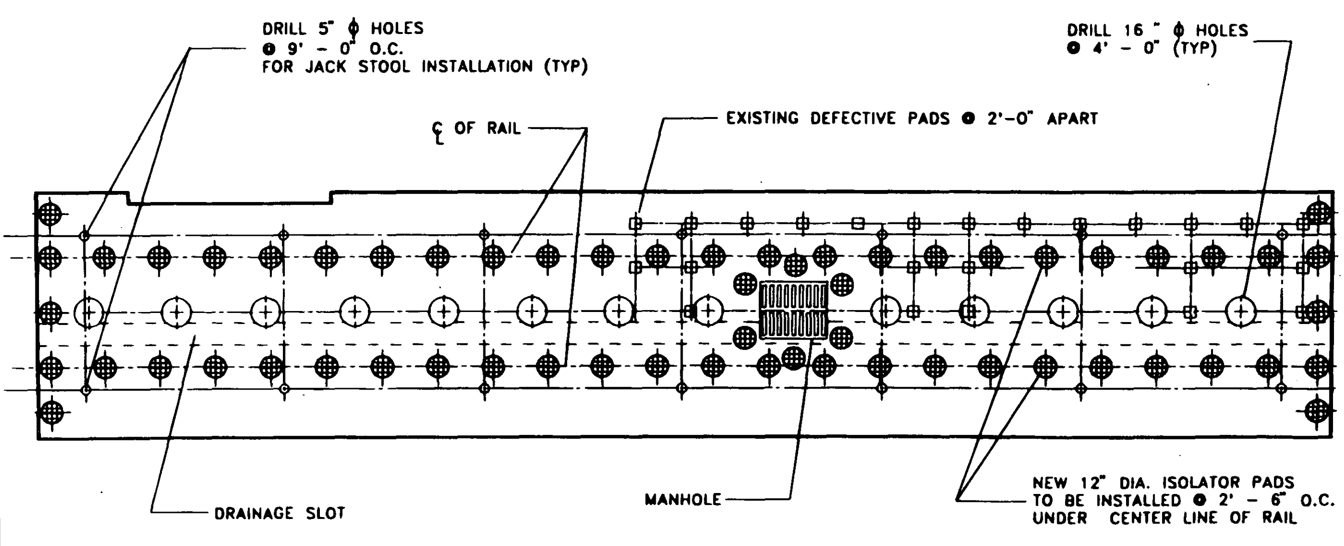
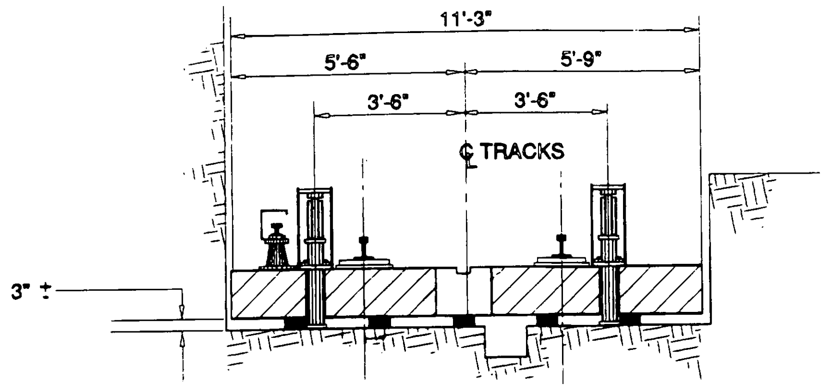
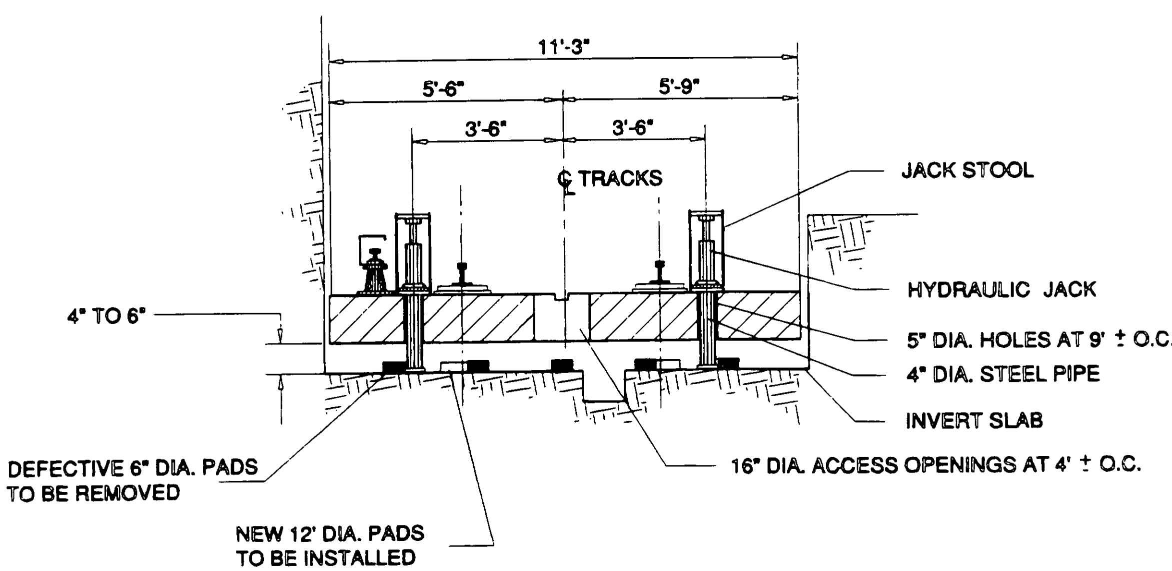


FIGURE 9 Typical layout of jacks and stools technique.



"WINDOW CUTTING" WITH JACK & STOOL
SLAB SECTION BEFORE LIFTING



"WINDOW CUTTING" WITH JACKS & STOOLS
LIFTED SLAB SECTION

FIGURE 10 Sections showing before and after retrofit.

TABLE 1 Floating Slab Retrofit Status

No	Contract Number	Section	Stationing	Length Feet	Slab Type	Track	Retrofit Method	Task Order	Date of Completion For				Tunnel - Trackwork Configuration
									Pad Repl.	Survey	Noise	Structure	
1	1A0062	A-6b	167+00 to 172+63	563	2	IB	B						Station
			167+00 to 172+63	563	2	OB	B						Station
			175+00 to 184+00	900	2	IB	A						Tunnel(circular)
			175+00 to 184+00	900	2	OB	A						Tunnel(circular)
			193+90 to 197+31	341	1	IB	C						#8 Double Crossover
			193+90 to 197+31	341	1	OB	C						#8 Double Crossover
			197+31 to 202+00	469	2	IB	B						Station
			197+31 to 202+00	469	2	OB	B						Station
			217+89 to 221+00	311	2	IB	A	4	05/16/93				Tunnel(circular)
			217+89 to 221+00	311	2	OB	A	1	11/07/92	06/14/93			Tunnel (circular)
2	1A0092	A-9b	305+25 to 308+80	355	1	IB	C						#8 Double Crossover
			305+25 to 308+80	355	1	OB	C						#8 Double Crossover
3	1C0031(a	C-4	86+80 to 88+30	150	2	OB	A						Tunnel(circular)
4	1C0051	C-5	145+37 to 147+15	178	1	IB	C						#15 Turnout
			145+04 to 146+82	178	1	OB	C						#15 Turbout
5	1C0062	C-6b	256+15 to 257+93	178	1	IB	C						#15 Turnout
			256+14 to 257+92	178	1	OB	C						#15 Turbout
			264+74 to 266+52	178	1	IB	C						#15 Turnout
			264+74 to 266+52	178	1	OB	C						#15 Turnout
6	1C0071	C-7	287+80 to 290+32	252	1	IB	C						#8 Double Crossover
			287+80 to 290+32	252	1	OB	C						#8 Double Crossover
7	1D0011	D-1	9+50 to 11+50	200	2	OB	A						Tunnel (circular)
		C-1	2+70 to 5+00	230	2	OB	A						Tunnel (circular)
		C-1	3+35 to 5+50	215	2	IB	A						Tunnel (circular)
8	1D0031(b	F-1	42+69 to 44+86	217	1	IB	C						#8 Double Crossover
			42+69 to 44+86	217	1	OB	C						#8 Double Crossover
			51+66 to 53+44	178	1	IB	C						#15 Turnout
			51+66 to 53+44	178	1	OB	C						#15 Turnout
9	1D0041	D-4a	100+02 to 103+20	318	2	IB	A	2	12/12/92	02/28/93	04/20/93		Tunnel (circular)
			100+02 to 103+20	318	2	OB	A	3	05/03/93	05/14/93			Tunnel (circular)
			105+80 to 106+97	117	2	OB	A	15	12/08/94				Tunnel (circular)
			106+97 to 107+55	58	2	IB	B	7	03/05/94				Vent Shaft (11'-3" slab)
			106+97 to 107+55	58	2	OB	B	18	01/28/95				Vent Shaft (11'-3" slab)
10	1D0042	D-4b	83+53 to 87+43	391	1	IB	C						#8 Double Crossover
			83+53 to 87+43	391	1	OB	C						#8 Double Crossover
11	1D0071	D-7	167+36 to 167+90	54	2	IB	B	14	11/21/94				Vent Shaft (11'-3" slab)
			167+36 to 167+90	54	2	OB	B	11	10/06/94				Vent Shaft (11'-3" slab)
			167+90 to 173+90	600	2	IB	B	10	08/02/94				Station
			167+90 to 173+90	600	2	OB	B	12	11/02/94				Station
			173+90 to 174+82	92	2	IB	B	9	05/24/94				Vent Shaft (11'-3" slab)
			173+90 to 174+82	92	2	OB	B	13	11/08/94				Vent Shaft (11'-3" slab)
12	1D0081(c)	D-8	174+82 to 175+42	60	2	IB	B	14	11/21/94				Vent Shaft (11'-3" slab)
			175+42 to 185+90	1048	2	IB	A	8	04/22/94				Tunnel (circular)
			174+82 to 175+42	60	2	OB	B	11	10/06/94				Vent Shaft (11'-3" slab)
			174+52 to 185+20	978	2	OB	A	6	02/27/94				Tunnel (circular)
13	1F0021	F-2a	59+60 to 62+30	270	2	IB	A	17	01/08/95				Tunnel (circular)
			59+70 to 62+10	240	2	OB	A						Tunnel (circular)
			66+00 to 67+70	170	2	IB	A	5	12/12/93				Tunnel (circular)
			65+80 to 67+80	200	2	OB	A						Tunnel (circular)
			70+80 to 72+70	190	2	IB	A	16	01/03/95				Tunnel (circular)
			71+20 to 72+30	110	2	OB	A						Tunnel (circular)
			84+00 to 86+18	218	2	OB	A						Tunnel (circular)
			86+18 to 86+60	42	2	OB	B						Vent Shaft (11'-3"slab)
		L-1	59+60 to 62+30	270	2	IB	A						Tunnel (circular)
			66+80 to 69+80	300	2	IB	A						Tunnel (circular)

(continued on next page)

TABLE 1 *(continued)*

14	1F0022	F-2b	86+60 to 87+42	82	2	OB	B						Vent Shaft (11'-3" slab)
			93+40 to 94+00	60	2	OB	B						Vent Shaft (11'-3" slab)
15	1G0031	G-3	427+31 to 432+81	550	2	IB	A						Tunnel (circular)
			427+27 to 432+77	550	2	OB	A						Tunnel (circular)
			437+00 to 442+90	590	2	IB	A						Tunnel (circular)
			436+91 to 443+56	665	2	OB	A						Tunnel (circualr)
			445+77 to 448+77	300	2	IB	A						Tunnel (circular)
			445+53 to 449+19	366	2	OB	A						Tunnal (circular)
16	1A0141	A-14	593+62 to 601+48	786	2	IB	B						Box Tunnel (11'-3" slab)
			593+62 to 601+48	786	2	OB	B						Box Tunnel (11'-3" slab)
17	1A0101	A-10a	329+00 to 336+00	700	2	IB	A						Tunnel (circular)
			329+00 to 336+00	700	2	OB	A						Tunnel (circular)
18	1A0131	A-13	569+25 to 569+75	50	2	OB	B						Box tunnel (11'-3" slab)
			569+75 to 571+75	200	1	OB	C						#8 Turnout
			571+75 to 573+25	150	2	OB	C						Box Tunnel (13'-3" slab)
			569+25 to 569+75	50	2	IB	B						Box Tunnel (11'-3" slab)
			569+75 to 571+75	200	1	IB	C						#8 Turnout
			571+75 to 573+25	150	2	IB	C						Box Tunnel (13'-3" slab)
			571+75 to 572+25	50	1	STOR	C						Central Storage Track (17'-0")
19	1K0021	K-2	205+68 to 210+18	450	2	IB	B						Box Tunnel (11'-3")
			205+68 to 210+18	450	2	OB	B						Box Tunnel (11'-3")
			220+48 to 223+09	261	1	IB	C						#8 Double Crossover
			220+48 to 223+09	261	1	OB	C						#8 Double Crossover

NOTES:

1. All defective isolator pads are made of polyurethane except for Sections C-4 and D-8 which are made of fiberglass
2. (a) Contractor for 1C0031 installed the floating slabs in Section C-4 No slab settlement was reported on 01/30/95. Not included in length count.
   (b) Contractor for 1D0041 installed the floating slabs in Section F-1.
   (c) Fiberglass pads by Transit Track, 60 Ft. (IB & OB) were polyurethane pads.
3. Method A: Applicable to circular tunnel sections, window cutting with jacks and beams. 10,209 feet (polyurethane). 2,026 feet (fiberglass).
   Method B: Applicable to wider slabs in stations and box sections, window cutting with jacks and stools. 6,548 feet (polyurethane).
   Method C: Applicable to special trackwork sections. 5,808 feet (polyurethane).
4. Length with defective polyurethane pads is 22,565 feet and with fiberglass pads is 2,026 feet.

nights have become the norm with the weekend as an option. Table 1 shows the typical progress status of this endeavor.

ACKNOWLEDGMENT

Tony Adams, Superintendent of Special Projects of WMATA's Office of Rail Track and Structure, deserves special recognition for his valuable contribution in solving this difficult maintenance problem. Acknowledgement is given to Mohammad Irshad and his staff of De Leuw, Cather and Company for their engineering support, Special appreciation is also expressed to Don Painter, Office of Rail Track and Structures, Ik Pyo Hong, and Ado Valge, Office of Engineering and Architecture, WMATA, for providing constructive guidance and Fady P. Bassily, WMATA, for continuing support.

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Calgary Light Rail Transit Surface Operations and Grade-Level Crossings

DAVE COLQUHOUN, JOHN MORRALL, AND JOHN HUBBELL

This paper presents an overview of Calgary light rail transit (LRT) surface operations and grade-level crossings. At present, the LRT system incorporates approximately 30 km (18.6 mi) of double track and 31 stations. Approximately 87 percent of the LRT system is composed of surface operation in a shared right-of-way. Outside of the downtown area, the LRT operates adjacent to and in the median of arterial roadways and in an existing rail corridor. In this environment, the LRT has priority over street traffic, preempting the traffic signals at intersecting roadways. Downtown, three LRT lines merge and run under line-of-site operation along the 7th Avenue Transit Mall along with transit buses and emergency vehicles. Although trains are not given special priority along 7th Avenue, traffic signal phasing provides progression to minimize delays as the LRT travels between stations. Based on experiences documented in this paper, it is demonstrated that LRT can operate harmoniously with private vehicles, pedestrians, and bicycles in the right-of-way of city streets. Strategies developed maintain an acceptable level of traffic operations at intersecting streets while giving priority to LRT operation through traffic signal preemption. Existing traffic signal and railway crossing equipment and control techniques have also been adapted to manage the interaction between LRT operations and private vehicle, pedestrian, and bicycle traffic at intersecting streets and LRT stations, and to accommodate nonstandard crossing configurations such as skewed intersections.

TRB has identified Task 1 of TCRP Project Integration of Light Rail Transit into City Streets to "gather, review and summarize published and unpublished information relevant to the problem for domestic and foreign LRT systems" (*1*).

The objective of this paper is to present an overview of Calgary light rail transit (LRT) surface operations and grade-level crossings. Included in this paper are the observed volumes for a range of surface-level crossing configurations.

BACKGROUND

Calgary is a city of approximately 738,000 people situated at the base of the Rocky Mountain foothills in southern Alberta, Canada. The city's economy is based on agriculture, energy, and tourism. Approximately one-third of the present employment is located downtown and in the inner city, one-third along the east industrial area, and one-third throughout the rest of the city.

Since the 1960s, Calgary's history has been one of overall steady growth, almost doubling in 20 years from a population of 400,000 in 1971 to 800,000 at present. The fact that the entire urban area is under the jurisdiction of the Calgary City Council makes Calgary truly a uni-city. This allows the city to exercise almost complete control over its urban environment, including its transportation system.

This combination of strong, continuous growth and uni-city jurisdiction has contributed to a successful LRT system in Calgary.

Before the 1940s, the downtown area was served primarily by streetcars. However, streetcar service was gradually phased out in favor of diesel and trolley buses on high-density routes. Streetcar service ended in 1951 and trolley bus service ended in 1974. Studies of rapid transit began in the mid-1960s, with the first plan recommending two legs of a heavy rail system and a downtown subway. After an evaluation of alternate rail transit alternatives and busways, LRT was selected on the basis of economics, system capacity, and the potential for influencing development.

In the early 1970s, Calgary instituted a new express bus service that was marketed as the Blue Arrow Express System. The Blue Arrow system acted as its own feeder in the farthest suburbs and connected with crossing feeder routes as it approached downtown. Limited stops between the outer suburbs and the downtown area gave it some of the characteristics of an express service. A series of park-and-ride lots was developed, with particular emphasis placed on proposed future rail corridors. Thus, the Blue Arrow and its feeder systems combined with park-and-ride lots to form a prototype for the development of the LRT system in terms of service and corridors.

IMPLEMENTATION OF LIGHT RAIL TRANSIT

In 1981, the initial 10.9-km (6.8-mi) LRT leg, extending from Anderson Road in south Calgary to downtown, opened for revenue service. In the downtown area the LRT operates along the 2-km (1.2-mi) transit mall on 7th Avenue. This transit mall is reserved for LRT, bus operations, and emergency vehicles only.

In 1985, a second 9.8-km (6.1-mi) leg was added to the northeast. The third leg of the system to the northwest was completed in 1987, extending from downtown to the University of Calgary. A 1-km (0.6-mi) extension of the northwest line was opened in 1990.

The existing LRT system, illustrated in Figure 1, is operated as two lines—Anderson to Brentwood (south to northwest) and Whitehorn to downtown (northeast). On weekdays, the LRT system carries approximately 100,000 passengers (378 boarding passengers per operating hour). Average weekday bus ridership is approximately 161,800 passengers (45 boarding passengers per operating hour). Information on peak-hour LRT ridership and level of service is presented in Table 1.

D. Colquhoun and J. Hubbell, Calgary Transit, City of Calgary, P.O. Box 2100, Station M, Calgary, Alberta T2P 2M5 Canada. J. Morrall, Department of Civil Engineering, University of Calgary, 2500 University Drive N.W., Calgary, Alberta T2N 1N4 Canada.

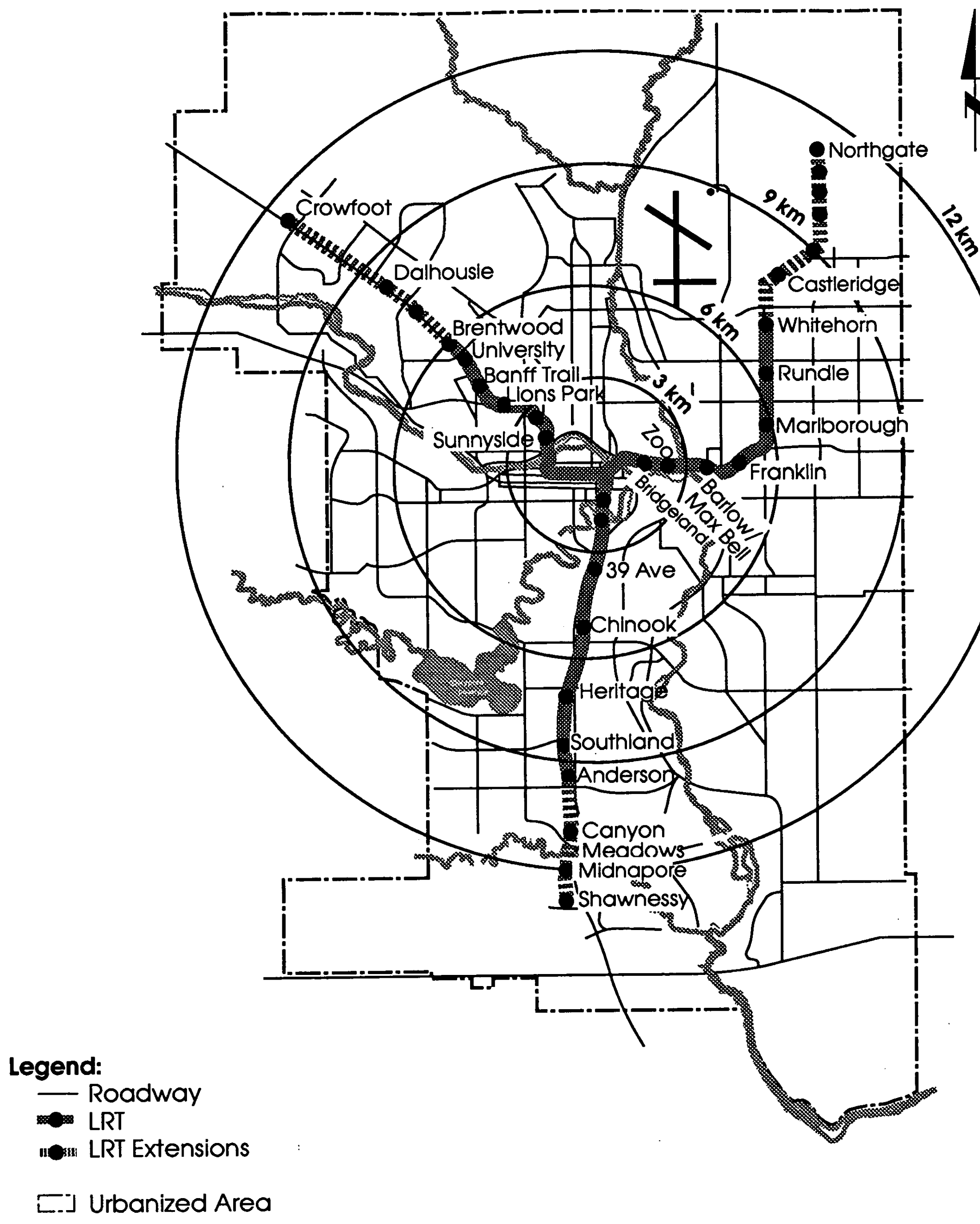

FIGURE 1 Calgary roadway and LRT networks.

OVERVIEW OF CALGARY LRT SURFACE OPERATION

Calgary's LRT system consists of approximately 30 km (18.6 mi) of double track, of which surface operation comprises 87 percent, 5 percent is on grade-separated bridges, and 8 percent is underground. Surface LRT alignments are located in the right-of-way of city streets, an existing railway corridor, and an exclusive right-of-way. There are 43 grade-level LRT/roadway crossings, of which 20 are controlled by railway gates and traffic signals, 10 by railway gates only, and 13 by standard traffic signals only. Pedestrian access to the four side-load platforms outside downtown is controlled by railway signals, pedestrian gates, and staggered bedstead railings. Access across the tracks to the staggered, side-load station platforms along the 7th Avenue Transit Mall is controlled by standard traffic and pedestrian signals at roadway intersections.

Outside downtown, train movements are controlled by an automatic block signal system, which allows only one train to occupy each section or "block" of track. At grade-level roadway crossings outside of the downtown, the trains preempt the normal operation of the traffic signals to allow uninterrupted movement between stations. Downtown, cross-street traffic and train and bus

TABLE 1 Observed Peak-Hour Volumes on Calgary LRT

LRT LINE	TRAINS PER HOUR PEAK DIRECTION (1-way) (T/H)	CARS PER HOUR (1-way) (C/H)	HEADWAY (SEC)	LENGTH OF TRAIN SET (# OF CARS)	PASSENGERS PER HOUR IN PEAK DIRECTION (PPH)	VOLUME/CAPACITY % IN PEAK DIRECTION Capacity = (C/H) X load factor (162 persons/car)
South	12	36	240 -360	3	4,200	72%
NW	11	33	240 -360	3	1,900	36%
NE	11	33	300 -360	3	3,300	62%

movements on 7th Avenue are controlled by conventional traffic signals.

Different methods have been developed to manage the interaction of train operations with automobile, pedestrian, and bicycle traffic within the street system and at LRT stations, as well as to accommodate nonstandard crossing configurations. This paper includes a discussion of experiences and lessons learned from surface rail operations in the following environments:

1. On-street LRT operations with bus and emergency vehicles on an exclusive transit mall (7th Avenue Transit Mall);
2. LRT operation in the median of an arterial roadway with full traffic signal preemption (northeast LRT operation on 36th Street N. E.);
3. LRT operation parallel to a major arterial roadway (9th Street S. W.);
4. Nonstandard LRT crossing configurations (e.g., skew angle crossing at 7th Avenue and 4th Street S. E.); and
5. Control of grade-level pedestrian access to side-load station platforms (Sunnyside, Lion's Park, and Banff Trail Stations) and a retrofit program for handicapped access to center-load station platforms (Erlton, Chinook, Heritage, and Southland Stations).

7th Avenue Transit Mall

Seventh Avenue South is located near the geographic center of downtown Calgary and has functioned for many years as the central spine for transit service. Downtown planning and transportation studies in the 1970s recommended that this street be transformed into a mass transportation corridor with 6th Avenue and 9th Avenue South acting as primary westbound and eastbound bus routes, respectively. A major step in this transformation occurred in 1973 with the implementation of a 1.6-km (1-mi) reverse-flow exclusive lane on 7th Avenue for westbound buses and a peak-period exclusive lane for eastbound buses. During this period, major transportation studies also identified 7th Avenue as an exclusive at-grade downtown transit corridor for LRT and bus operations. The contraflow bus lane ended in 1979 when construction commenced on the south LRT leg. The conversion of 7th Avenue to an exclusive transit mall was completed in May 1981 with the commencement of LRT service.

The 7th Avenue Transit Mall extends over 14 blocks downtown Calgary, from 4th Street East to 10th Street W.—a distance of approximately 2 km (1.2 mi). Within this area, trains from the south and northwest LRT legs (Route 201) and northeast leg (Route 202) merge and operate on the street with buses and emergency vehicles (see Figure 2). An area equivalent to the two center lanes on a four-lane downtown roadway is used for LRT traffic, with the outside curb lanes reserved for buses and LRT stations. Eleven unidirectional raised platforms have been strategically placed every three to four blocks along the corridor, and in these areas buses must use the two center lanes to travel around the stations.

Currently, Routes 201 and 202 operate at peak-hour headways of 5 and 6 min, respectively (22 trains per direction—total both lines), in three-car train sets and carry a combined ridership of 7,500 passengers per hour (peak hour, peak direction) along 7th Avenue. The combined train frequency is every 2 to 3 min. In addition, five bus routes operate along 7th Avenue between 1st Street E. and 8th Street W., producing a peak-hour bus volume of 25 buses per direction. Table 2 presents a summary of the grade-level roadway and pedestrian crossings and the p.m. peak-hour crossing volumes along 7th Avenue.

The traffic signals along the 7th Avenue Transit Mall function as part of the downtown system, which is under centralized computer control. LRT trains are not given special priority at signals downtown; however, a signal progression has been designed along 7th Avenue to minimize delays as the LRT travels between stations. The characteristics of the 7th Avenue signal operation are presented in Table 3.

It is also noted that pedestrians are restricted to sidewalks and may legally cross the transit corridor at crosswalks only. At selected locations where jaywalking has presented a problem (e.g., 3rd Street S.E., 9th Street S.E., and between 1st Street E. and Centre Street), post-and-chain barriers, pedestrian gates, and bedstead railings have been installed adjacent to the sidewalks to channel pedestrian flows and discourage midblock crossings. In addition, the LRT stations on 7th Avenue may be accessed through an extensive network of elevated pedestrian walkways (the PLUS 15 system) that link major office buildings and connect with designated parking corridors on 4th Avenue South and 9th Avenue South (see Figure 3).

Transit operations on the 7th Avenue Transit Mall have been investigated using TRANSITSM (*2,3*), an event-by-event simula-

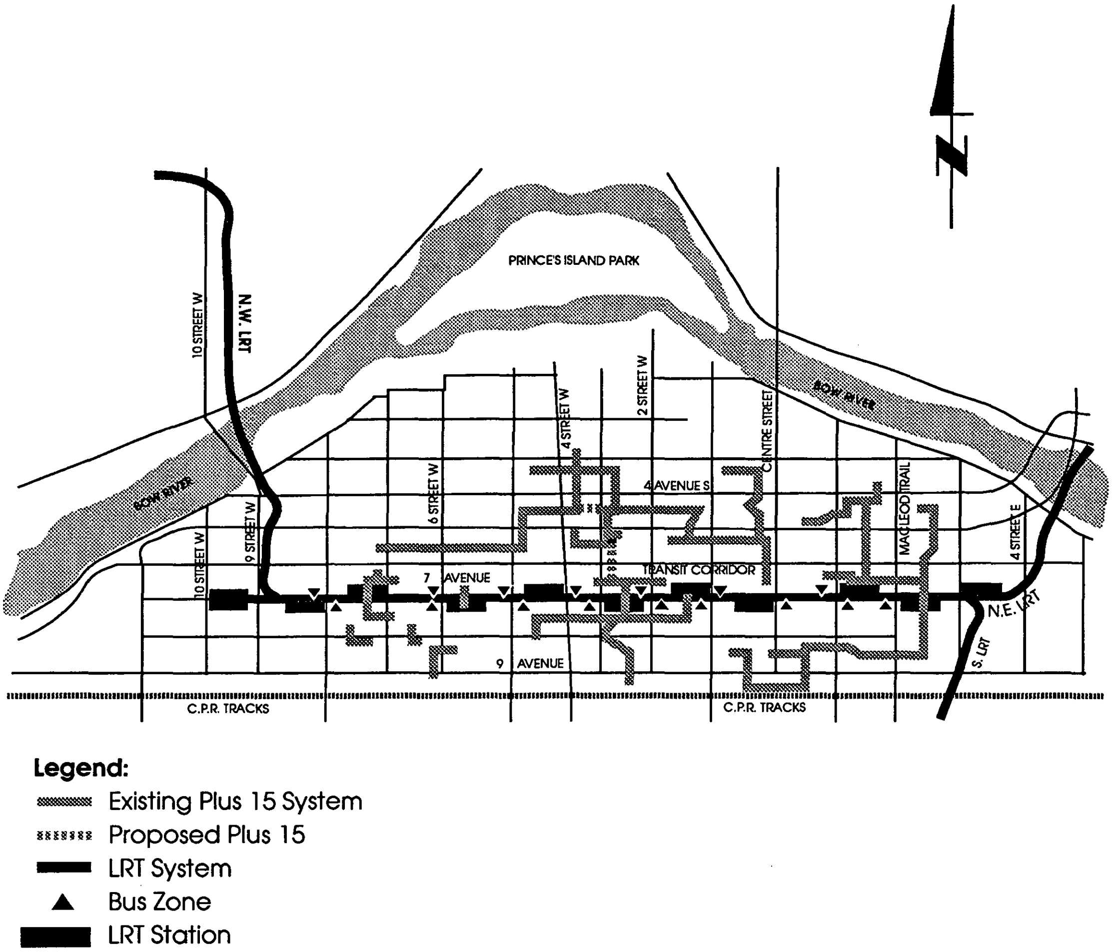

FIGURE 2 7th Avenue South Transit Mall.

tion model written in the General Purpose System Simulation computer language. The simulation model is based on the following assumptions related to the logic of traffic operations:

- Trains cannot be operated so that two or more trains bunch together at any station. Therefore, the maximum station capacity is one train, whereas the capacity of a bus stop depends on the length of curb space provided.
- No train can be overtaken by buses at any station because of the system geometry.
- Buses interact with trains in the inner lanes and at stations but only LRT is permitted to dwell at the stations.
- The queue discipline is "first-in-first-out" to allow vehicles to be processed sequentially.
- Pedestrian flows on the simulated area are not explicitly considered in the model.
- The running, dwell, and terminal layover times are random quantities with empirically determined means and standard deviations.
- No two trains can occupy the same block of street at any time to avoid blockage of upstream intersections.

TRANSITSM was developed with over 3,500 statements consisting of five bundles, specifically, eastbound transit, westbound

TABLE 2 7th Avenue Transit Mall Characteristics

NUMBER OF GRADE LEVEL VEHICULAR CROSSINGS	MAXIMUM VEHICULAR CROSSING VOLUMES (VEHICLES PER HOUR)	NUMBER OF PEDESTRIAN CROSSINGS	MAXIMUM PEDESTRIAN VOLUMES (PERSONS/ HOUR)	PEAK PERIOD TRAIN FREQUENCY (TRAINS/ HOUR)	PEAK HOUR BUSES 2-WAY
14	320 - 2100 (avg: 1020)	26	150 - 950 (avg: 560)	45	50

TABLE 3 7th Avenue Transit Mall Signal Operation

TIME PERIODS	CYCLE LENGTH (SEC)	SIGNAL GREEN SPLIT FOR 7th AVENUE (SEC)
A.M. Peak Period	70	24 - 46
P.M. Peak Period	80	24 - 56
Off-Peak (day)	70	24 - 46
Night	60	24 - 36

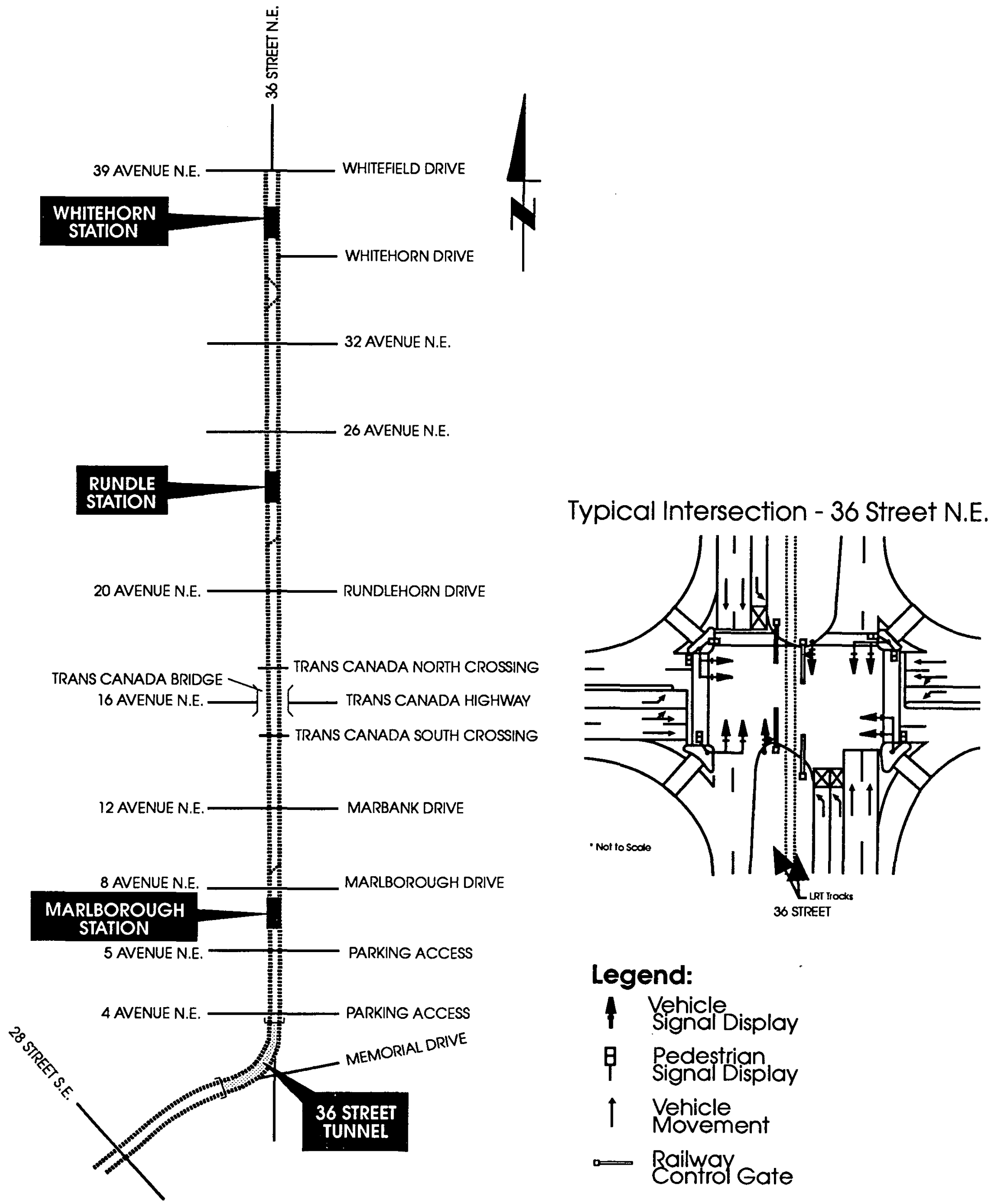

FIGURE 3 Northeast LRT—36th Street N.E. corridor.

transit, traffic signal plans, traffic on the 12 intersecting streets, and a simulation tuner that regulates the duration of each experimental run. The model is capable of simulating 2 hours of a.m. peak, 6 hours of midday, 3 hours of p.m. peak operation, and 11 hours of combined operation per day. The computer to real-time ratio is 1:100.

The findings of the simulation analysis indicated that the surface transit mall has a threshold capacity beyond which an unstable transit operation exists. The key constraints on train capacity are at the switch points on the east and west ends of 7th Avenue where Routes 201 and 202 enter and exit the transit mall. The threshold capacity was reached at a headway of 4 min. per line or a one-way capacity of 30 trains per hour for LRT operation only. With a 5-min. headway per line, the transit mall capacity (one-way) is 24 trains per hour and 30 buses per hour. This threshold slightly exceeds the existing operating conditions on the transit mall, at which LRT headways are 5 and 6 min., respectively, per line (22 trains per hour) and bus volumes are 25 buses per hour.

Simulation also demonstrated that transit operations on the mall became unstable (i.e., bunching of trains and an increase in travel time) for combined train headways less than 2 min.

When the present use of the transit mall by LRT and buses becomes impractical, it will necessary to divert bus operations from 7th Avenue to other downtown streets. Over the long term, expansion of the downtown platforms to accommodate four-car train sets will be required. In addition, construction of a LRT subway beneath 8th Avenue S.W. (at an estimated cost of over $200 million) could also be considered to provide additional transit capacity.

Northeast LRT Operation on 36th Street N.E.

The operation of the Northeast LRT in the 36th Street N.E. corridor provides a case study of how surface LRT operations may be integrated within the median of a major arterial roadway with traffic signal preemption.

Thirty-sixth Street N.E. is a four-lane arterial roadway that extends through an intensely developed area containing extensive commercial development and medium-density residential development. Within this corridor, there are 10 grade-level intersection crossings by LRT over a 3.6-km (2.2-mi) distance, as shown in Figure 2.

The average daily traffic flow on 36th Street N.E. is approximately 35,000 to 40,000 vehicles, with the daily directional split at about 50/50. The presence of major commercial land uses generates a high volume of left-turn and cross-street traffic in the area between 4th Avenue and 12th Avenue N.E. and the intersections at 20th Avenue/Rundlehorn Drive, 26th Avenue, and 32nd Avenue N.E. A summary of p.m. peak-hour train, vehicular, and pedestrian volumes at the 10 at-grade crossings is presented in Table 4.

The track alignment for the northeast LRT line is located in the median of 36th Street N.E. Continuous concrete barriers and chain-link fencing near the stations separate LRT and automobile traffic and discourage jaywalking. All intersections are controlled by railway gates and preemptive traffic signals that give priority to approaching trains. Any "green time" lost to vehicles and pedestrians because of LRT signal preemption is subsequently restored once the train has cleared the crossing. Pedestrian access to the three center-load LRT stations is accommodated by pedestrian bridges that are accessed by stairways and spiral ramps. The maximum LRT operating speed on 36th Street N.E. is 80 km/hr, whereas the posted speed limit for vehicular traffic is 60 km/hr.

The 10 grade-level intersections are signalized with left-turn phasing on 36th Street and approach phasing on the side streets so that the signal shows green for both through and left turn in one direction, then switches to through and left turn for the opposite approach. Signal controllers are connected to the central traffic control computer. The central computer selects timing plans by time of day, but cycle length and splits are determined by the traffic signal controllers. There are stop-line loop detectors on all intersection approaches.

On weekdays, the traffic signals on 36th Street N.E. are only coordinated during off-peak hours. With the combined train headway during peak periods averaging 3 min and the existence of LRT preemption, it is not practical to operate coordination plans during peak periods. However, the signals are coordinated throughout the weekend period, when trains operate at headways of 12 to 15 min.

Although the current LRT operation on 36th Street N.E. is reasonably efficient, there are significant delays to side street and left turning traffic from 36th Street N.E. at certain times because of long gate warning times or consecutive gate activations from closely spaced trains. To address these issues, a recent study (*4*) recommended that the following measures be implemented to fine-tune existing operations:

Reduce Basic Gate Warning Time

Currently, the gate warning time is set for the greater of 20 sec or the time required for the pedestrian to walk the length of the crosswalk that crosses the LRT tracks. Using these criteria, gate warning times along 36th Street N.E. average 25 sec.

The grade-level LRT crossings along 36th Street are located within signalized intersections at which no vehicles normally stop; they are within the line of sight of train operators, who are accustomed to in-street operation. It takes approximately 14 sec to completely lower the gates after activation of the flashing lights and bells, and the traffic signals show a red light to all opposing traffic approximately 6 sec after the start of the warning devices. In short, before the railway gates are lowered, no more vehicles can get onto the tracks and no vehicles should be queued on the tracks.

On the basis of these factors, it was determined that the gate warning times could be reduced a minimum of 15 sec, or the actual time required for a pedestrian to reach the safety of the median island before the LRT arrives at the crossing. Using a pedestrian walking speed of 1.22 m/sec (4 ft/sec) all intersections with an east-west pedestrian crosswalk would require at least 18 sec for pedestrian clearance. Fine-tuning gate warning times in this manner could reduce some gate warning times by as much as 10 sec.

Raise Gates Earlier

At present, the gates begin to rise after the rear of the train leaves the island circuit. When the gates start to rise, the traffic signals time 6 sec of yellow and red light clearance before a green signal is given to opposing traffic.

It was concluded that the gates could safely start to rise 1 sec after the train first enters the crossing. This change would reduce the total preemption time by 4.5 sec for a three-car train crossing at 80 km/hr.

TABLE 4 36th Street N.E. LRT Corridor Traffic Characteristics

GRADE LEVEL ROADWAY CROSSING	COMBINED PEAK HOUR TRAIN FREQUENCY (SEC)	PEAK HOUR TRAFFIC VOLUME CROSSING 36TH STREET VPH (2 - WAY)	PEAK HOUR PEDESTRIAN VOLUME CROSSING 36TH STREET PERSONS/HR (2 - WAY)
4th Street N.E.		288	12
5th Avenue N.E.		607	53
8th Avenue/Marlborough Dr. N.E.	180	519	137
12th Avenue/Marbank Dr. N.E.	-360	981	15
16th Avenue EB ramp 16th Avenue WB ramp		129 223	NA
20th Avenue/Rundlehorn Dr. N.E.		1422	54
26th Avenue N.E.		922	41
32nd Avenue N.E.		1898	49
Whitehorn Drive N.E.		206	28

Install Advance Vehicle Detectors

Currently, only stop-line vehicle detectors are used at traffic signals. More efficient traffic signal operation could be achieved with the installation of advance detectors.

Educate LRT Controllers and Operators

It was concluded that the effect of train operations on the intersection operation could be minimized by careful attention to train departure times and minimizing between-station stops at switch points. This training, in addition to recent initiatives to improve communication between LRT controllers and operators, has improved the efficiency of LRT operations and reduced the delay to vehicular traffic at grade-level roadway crossings.

LRT Operations on 9th Street S.W.

The operation of the Northwest LRT on 9th Street S.W. at the west end of the 7th Avenue Transit Mall is an example of surface LRT operation adjacent to an arterial roadway with major cross-street traffic and standard traffic signal control and railway lights and bells. Figure 4 shows this particular surface operation (note that 9th Street S.W. is one way southbound). In the p.m. peak hour, a total of 320 vehicles per hour cross the LRT in one direction, and 150 pedestrians per hour cross both the transit mall and the northwest LRT line. The corresponding volumes on the transit mall in the p.m. peak hour are 45 trains and 50 buses per hour. The northwest LRT line carries 22 trains per hour during the p.m. peak hour.

LRT Operations on 7th Avenue and 4th Street S.E.

The intersection of 7th Avenue and 4th Street S.E. at the east end of the 7th Avenue Transit Mall is an example of nonstandard LRT crossing configuration in which the northeast LRT operates on a skew angle through the intersection. The direction of traffic flow and the general configuration of the crossings at the east end of the transit mall are shown in Figure 5.

At the 3rd Street east location, there are 45 trains per hour in both directions in the p.m. peak hour. At the 6th Avenue location, there are 22 trains per hour in the p.m. peak period and 14 buses per hour. This is close to the capacity of 48 trains per hour as determined by simulation.

Grade-Level Access to LRT Stations

The experience gained from construction and operation of each of the LRT lines has resulted in changes in the scale and design of Calgary's LRT stations.

The initial south LRT line includes six center-load stations that are accessed by stairways and a single set of escalators that operate in the peak travel direction. No provision was made to include elevators and ramps to accommodate people with disabilities at these stations; however, equivalent funds were committed by the City Council to upgrade the specialized, door-to-door Handi-Bus service. Downtown, short stairways and access ramps were constructed at the 7th Avenue stations.

The design of the second leg of the LRT system to the northeast incorporated the LRT alignment in the median of an expressway and major arterial roadway. The seven center-load stations on this

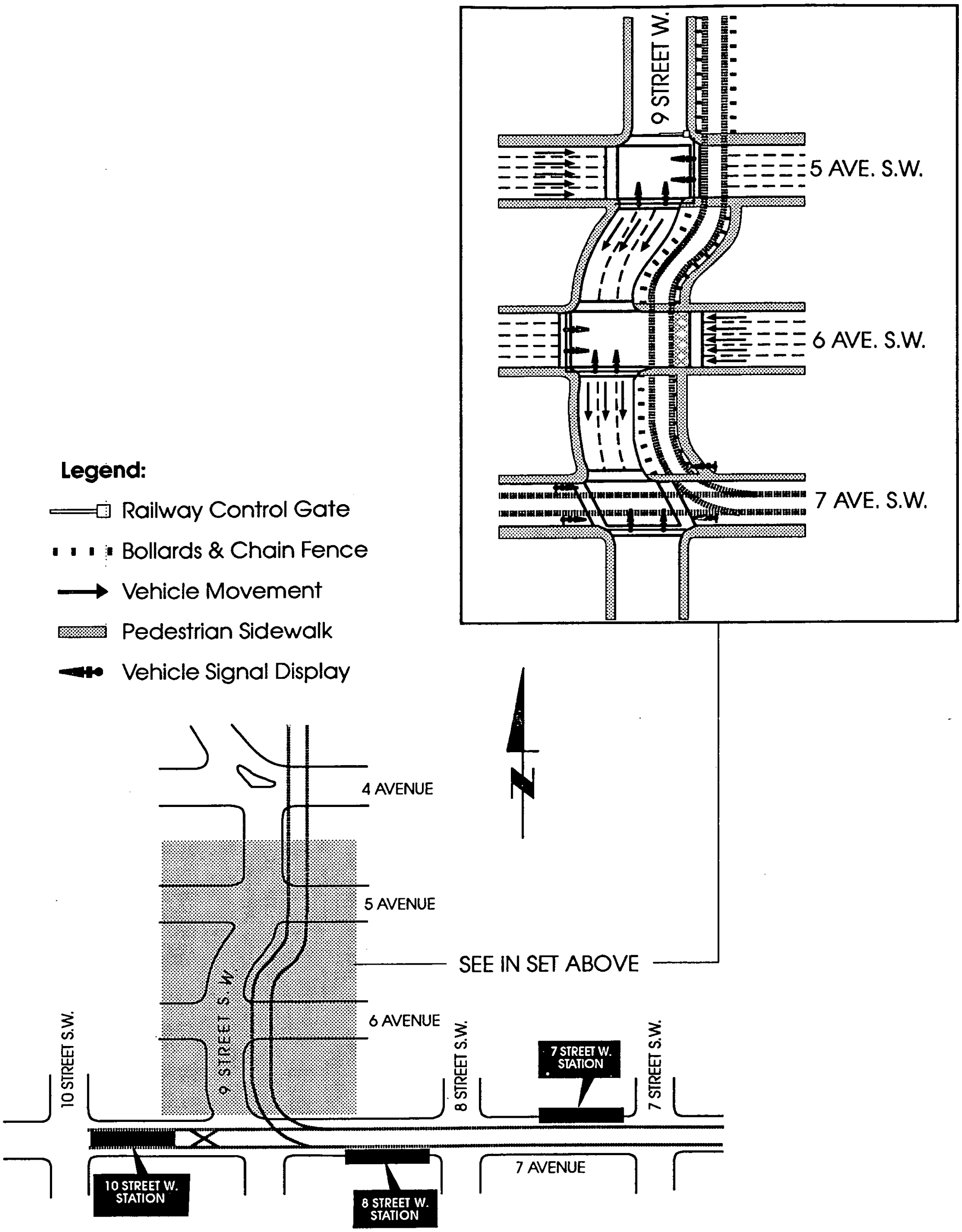

FIGURE 4 LRT operations on 9th Street S.W.

line are fed by stairways and ramps spanning the roadways. Within the stations, an elevator and two sets of escalators link the fare process area to the platform.

The design of the newest phase of the LRT system in northwest Calgary reflects lessons learned from the first two LRT lines. Stations in established inner-city communities (e.g., Sunnyside, Lions Park, and Banff Trail) incorporate low-scale, side-loading platforms with grade-level access across the LRT tracks. As illustrated in Figure 6, railway signals, pedestrian gates, and staggered bedstead railings provide pedestrian crossing protection at designated access points. These grade-level crossings enhance transit customer access by providing short, direct travel paths to the LRT platforms and also form part of the community pathway and bicycle network that link northwest communities. Large signs have also been installed to alert customers to check both directions before proceeding across the tracks. Provision of grade-level access to the northwest stations has greatly improved customer access. As well, standard railway crossing signals and pedestrian gates have been effective in providing crossing protection for the volume of pedestrian and bicycle traffic that crosses the LRT corridor.

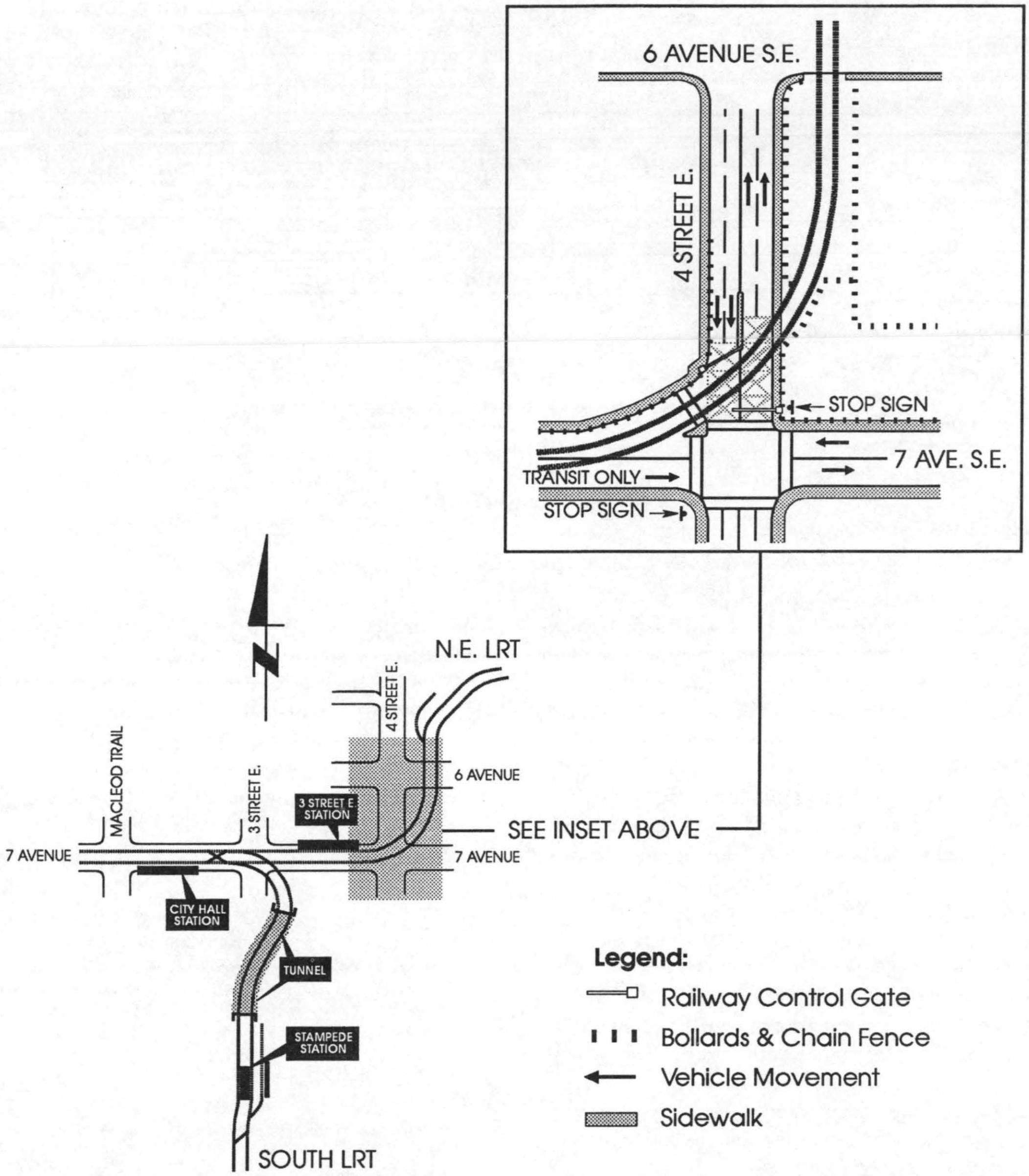

FIGURE 5 7th Avenue and 4th Street S.E.—skewed crossing.

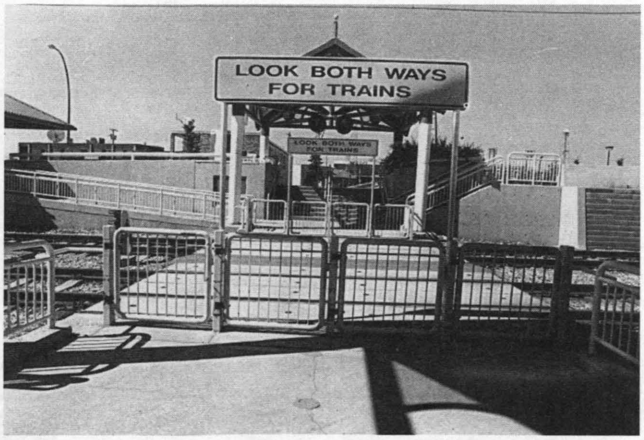

FIGURE 6 LRT station grade-level access.

Based on the favorable experience with grade-level access to the northwest LRT stations, new grade-level pedestrian connections are being constructed to accommodate handicapped access to the south LRT stations. The new access connections incorporate a ramp and a concrete apron linking the south end of the station platform to the park-and-ride lots, as shown in Figure 7. There is a single grade-level crossing of the southbound LRT track, which is controlled by railway signals and staggered bedstead railings. A "help" phone, a stand-alone ticket validator, and new lighting are provided at the foot of the new stairway and ramp.

CONCLUSIONS

Based on more than a decade of operating experience, Calgary Transit has demonstrated that LRT technology can be integrated

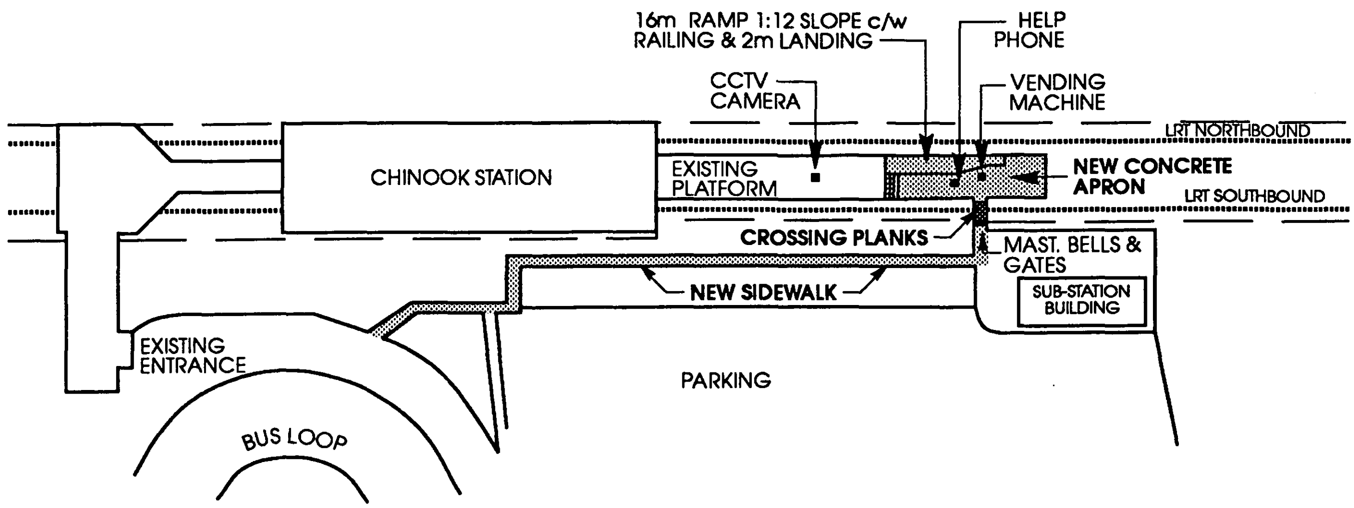

FIGURE 7 Chinook LRT station—handicapped access.

with the rights-of-way of city streets. The ability to adapt surface LRT operations within a variety of environments ranging from the exclusive transit mall downtown and the right-of-way of major arterial roadways has been a key factor in the economical development of the Calgary LRT system. Adoption of signal preemption for LRT operations at grade-level crossings and development of a comprehensive, balanced range of access modes (e.g., feeder bus, park-and-ride, automobile passenger drop-off, and walking and cycling) has also created an integrated system that is competitive with the private automobiles for traveling downtown (*5*).

Strategies have been developed to maintain an acceptable traffic operation within shared LRT and roadway rights-of-way by fine-tuning traffic signal and railway gate controls at grade-level roadway crossings and developing simulation models to establish threshold capacities for LRT operations downtown. Existing traffic signals, railway crossing equipment, and other traffic and pedestrian control techniques have also been adapted to manage the interaction between LRT operations and private vehicle, pedestrian, and bicycle traffic at intersecting streets and LRT stations and to accommodate nonstandard crossing configurations such as skewed intersections. To enhance pedestrian safety along the 7th Avenue Transit Mall, posts and chains, bedstead barriers, and No Jaywalking signs have been installed at several locations. In addition, Calgary Transit has worked with the local police to obtain more support in enforcing the jaywalking laws. These actions have led to a gradual reduction of level crossing accidents.

Other actions that have enhanced safety include the development of an in-house grade-level crossing committee involving Calgary Transit management and front-line operator membership to review all grade-level crossings. Public awareness campaigns have also been developed to reinforce existing LRT safety features.

REFERENCES

1. *Integration of Light Rail Transit Into City Streets.* TCRP Project A.5, FY 93, Transit Cooperative Research Program. TRB, National Research Council, Washington, D.C., 1993.
2. Babalola, A., and J. F. Morrall. Capacity Investigation of a Surface Transit Mall. *Transportation Planning and Technology*, Vol. 10, 1985, pp. 99–111.
3. Babalola, A., and J. F. Morrall. *Simulation of Surface LRT Operation on a Mixed Traffic System.* Modelling, Simulation and Control, C. AMSE Press, Vol. 26, No. 1, 1991, pp. 1–34.
4. D. K. S. Associates. *Reducing LRT Impacts for Traffic on 36 Street N.E.* Final Report, Prepared for the City of Calgary Transportation Department. Sept. 1991.
5. Hubbell, J., D. Bolger, D. Colquhoun, and J. F. Morrall. *Access Mode Planning for the Calgary LRT System.* Compendium of Papers from the 1992 Annual I. T. E. Meeting, Washington, D.C.

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Cost of Light Rail Collision Accidents

CHRISTOPHER D. PORTER, MARK M. HANSEN, AND ABNER GALLARDO

This paper estimates the full costs of collision accidents on the Santa Clara County light rail system in San Jose, California. Per-accident costs to the transit agency are estimated, including money paid out and staff time spent, based on 6 years of accident records. Costs are estimated for injury and noninjury accidents and by accident type. Additional costs to society are also estimated based on previous studies of highway crash costs. The average cost of an injury accident was found to be $206,411 to society as a whole, of which $3,972 was to the transit agency. The average cost of a noninjury accident was found to be $9,111 to society as a whole, of which $1,872 was to the transit agency.

The purpose of this paper is twofold: first, to provide a methodology for estimating the costs of collision accidents on light rail systems and second, to present a case study of light rail collision costs on the Santa Clara County Transportation Agency (SCCTA), located in San Jose, California. Comprehensive collision costs are estimated both to the TA and to society as a whole.

This study is part of a larger project, funded by the California Department of Transportation (Caltrans), on the application to light rail transit of safety measures that use Intelligent Vehicle Highway Systems (IVHS) technology. Renewed interest in public transit among transportation planners and government agencies has led to a renaissance of light rail in recent years, particularly in California. Nine U.S. and Canadian cities have built light rail systems in the past 2 decades, and many others are either planning or debating such systems. California has four recently built systems, in San Jose, Sacramento, San Diego, and Los Angeles, in addition to the classic streetcar lines operated by the San Francisco Municipal Railway (Muni).

Although light rail transit has a good safety record, there are opportunities to further reduce the number and severity of accidents involving light rail vehicles. In selecting countermeasures to use, however, the benefits of accident reduction must be weighed against the costs of implementation.

To perform such an assessment, integrated models of collision occurrence, severity, and cost are required. These models must be sensitive to the effects of countermeasures in reducing the incidence and severity of collisions involving light rail vehicles and must reflect the cost savings of such reductions. The larger study therefore includes accident analysis to identify hazard conditions and critical events leading to collisions. An extensive set of possible countermeasures, ranging from simple refinements of existing procedures to applications of advanced sensor and actuator technologies, has also been identified. Assessment of the potential effectiveness and real-world feasibility of these countermeasures is presently underway. When this is complete, it will be possible to use the system of models described earlier to estimate the economic value of countermeasures, both in the aggregate and by cost category. When such estimates are combined with estimates of countermeasure cost (which will be developed at a later stage of the study), a rational basis for selecting which countermeasures to implement will be established.

C. D. Porter and M. M. Hansen, University of California, Berkeley, 215 McLaughlin Hall, Berkeley, Calif. 94720. A. Gallardo, University of Washington, 820 42nd Avenue South, Seattle, Wash. 98118.

BACKGROUND

Safety Investment

Safety investment decisions can be based on a variety of criteria (*1,2*):

1. Cost-benefit ratio: total costs and total benefits are quantified in dollar values, and investment is made to the point at which incremental investment equals the incremental benefit obtained. Although theoretically appealing, cost-benefit analysis is rarely applied. Many benefits of accident reduction are difficult to label with a dollar value, and attempts to do so can be highly controversial.
2. Cost-effectiveness: projects are ranked based on the amount of safety improvement per dollar spent. If a fixed level of resources is available, projects are completed in ranked order, starting with the most cost-effective, until resources are used up. In this case, the benefits do not have to be monetized; they can be lives saved, injuries prevented, and so on. An example of cost-effectiveness analysis is the prioritization of railroad-highway grade crossing improvements.
3. Threshold safety level: a minimum acceptable level of safety is set. This is commonly done based on a comparison to analogous systems or to previous system performance. An alternative approach, rarely used in practice, is to conduct an explicit risk-benefit analysis (*1*).
4. Industry and government standards, both formal and informal, for vehicles, stations, traffic control devices, and operating procedures are followed. Rather than prescribing an acceptable level of safety, these standards promote behavior and decisions on the part of managers and line personnel consistent with "safe" operation.
5. Decisions are made on an ad-hoc, perceived-need basis.

In practice, transit agency decisions in matters related to safety are characterized by the last two of these approaches. Light rail technology extends back to the streetcar era, so there is extensive experience on which to base standards for safe equipment, facilities, and operations. With these as a baseline, individual agencies take further steps to increase safety by responding to problem areas revealed by the occurrence of accidents and near-misses, as well as the perceptions of agency personnel.

Cost-benefit analysis cannot and should not replace these procedures, but it can extend the capabilities of transit operators to identify cost-effective actions to improve safety. Analyses of the incidence and severity of light rail collisions will, at a minimum, validate more subjective assessments of safety problem areas and

may substantially alter them. Evaluations of the economic costs of these events make it possible to determine whether resources should be redirected to safety from other areas, and if so, how such resources should be spent. Furthermore, by distinguishing costs to the agency from costs to society, it is possible to determine when a safety expenditure is in the agency's own narrow self-interest and when it may be appropriate for society to encourage or subsidize such an expenditure. The latter is particularly important in light of the increased flexibility of regional planning agencies in allocating federal transportation funds resulting from Intermodal Surface Transportation Efficiency Act (ISTEA) legislation, as well as increasing pressure from the Clinton Administration that all transportation investments using federal funds undergo cost-benefit analysis (*3*).

Accident Cost Analysis

A growing body of literature exists on the costs of highway accidents. Studies by the National Safety Council, the National Highway and Traffic Safety Administration, and the FHWA have attempted to quantify the total societal losses, both economic and noneconomic, due to highway accidents (*4–6*). The most recent study, *The Cost of Highway Crashes*, estimated the annual comprehensive cost to be $334 billion in 1988 (*6*). As the authors point out, this cost represents the maximum rational investment in highway safety above and beyond current levels. The present study draws on this work for a number of costs that could not be found directly.

Although considerable safety-related work has been done in the transit field, to the best of the authors' knowledge no thorough study exists on the costs of crashes involving transit vehicles. Also, although previous reports have recognized the need for evaluating transit safety measures on a cost-effectiveness basis (*7*), a methodology for doing so has not yet been proposed.

SYSTEM OVERVIEW

Santa Clara County's light rail line began running in 1987 and by 1991 had expanded to the 21-mi (33.8-km) system currently in operation. The system has three major sections: a separate right-of-way in the median of North First Street, with signalized grade crossings at intersections; a downtown pedestrian mall; and an exclusive right-of-way along the median of the State Route 87 freeway. Maximum operating speeds on each section are 35, 10, and 55 mph (56, 16, and 89 km/hr), respectively. The system layout has much in common with that of other recently constructed light rail lines in North America.

Through 1993, a total of 169 collision accidents with motor vehicles, pedestrians, and bicyclists have occurred on the system. Of these, 50 have resulted in one or more minor injuries, two in a severe injury, and three in a fatality (one was a possible suicide). Collision accidents per vehicle-mi have steadily declined to nine per 100,000 vehicle-mi (5.6 per 100,000 vehicle-km) in 1993. This compares favorably with other light rail properties (*8*). Despite the exclusive use of signalization and extra signage for left turns along North First Street, the majority of accidents (63 percent) have resulted from drivers turning left in front of parallel-running trains, and 10 percent are from mirror-image, right-turn accidents on the downtown pedestrian mall. The predominance of so-called "left-turn" accidents is common to most light rail transit properties (*9*).

METHODOLOGY

For this analysis, accident costs are broken down into two categories: costs that accrue directly to the transit agency and costs that are borne by all other elements of society. Agency costs can be further categorized as direct disbursements per accident, direct disbursements per year, or time contributions by agency employees. Categorization may vary among transit agencies; for example, some process claims in-house, and others contract out for claims work. The cost categories identified for this analysis are summarized in Table 1.

Direct agency costs for each accident were estimated from agency records whenever possible. Estimates of typical staff time spent per accident were provided by light rail division staff. Rider delay per accident was also estimated from agency records. Other costs incurred by individuals, as well as emergency response costs, were estimated using national data from *The Cost of Highway Crashes*. Average costs per accident were then calculated based on whether or not the accident resulted in injury. Ideally, costs would be broken down using a more refined injury scale (including differentiation by minor injury, severe injury, and fatality); however, a lack of data on severe injuries precluded this. Costs were also tabulated based on accident type. Disaggregation of costs by accident characteristics should be helpful in assessing the cost-effectiveness of specific countermeasures.

Direct Agency Costs

Property Damage, Claims Administration, Claims Payments, Legal Expenses

Itemized data were available from agency records for July 1990 through the end of 1993, a total of 76 accidents. SCCTA contracts with an outside adjustor to estimate damages and to process claims against other parties and claims against the agency. Therefore, administrative costs and claims paid out by the agency for property damage and bodily injury were available on a per-accident basis. Legal costs and attorney fees were also obtained from internal memos. Data from previous years were inflated to 1993 dollars based on the Consumer Price Index (*10*). Claims payouts by the agency were incurred in roughly 10 percent of cases, reflecting that the transit agency is rarely found legally liable in light rail collision accidents. On the contrary, the transit agency was able to partially or fully recoup costs from the other party in a substantial proportion of cases.

From a societal perspective, claims paid and received by the transit agency are transfer payments rather than actual costs. Therefore, in determining social costs, claims paid by the agency are subtracted from nonagency costs, and claims paid to the agency are added to nonagency costs. Such transfer payments do not change the overall cost to society.

Operator Overtime

When an accident occurs, SCCTA relieves the operator for 1 to 2 hr to impound the vehicle and fill out reports. The operator is replaced from a pool of "extraboard" operators waiting on standby. Most extraboard operators are used for purposes unrelated to collision accidents (such as sickness and no-shows), so it is doubtful that this

TABLE 1 Description of Cost Categories

Cost Category	Description	Payer	Source of information
Agency property damage	Damage to LRVs and other agency property	Transit Agency	Agency records
Claims administration	Damage adjustment; processing of claims for and against agency	Transit agency	Agency records
Claims payments	Claims for bodily injury and property damage paid out by agency	Transit agency*	Agency records
Claims received	Claims payments received by agency from individuals	Society**	Agency records
Legal & court expenses	Legal counsel and court fees paid by the agency	Transit agency	Agency records
Operator overtime	Overtime paid by agency to LRV operators	Transit agency	Estimated by light rail division staff
Supplementary service	Bus bridge or van shuttle around accident scene	Transit agency	Occurrences from agency rcords; service costs estimated
Revenue loss	Immediate or long-term revenue loss due to lost ridership	Transit agency	Time-series analysis of ridership
Catastrophic Insurance	Agency insurance against catastrophic liability or property damage	Transit agency	Agency records
Accident response	Staff time spent responding to scene, filling out reports, and investigating accident	Transit agency--time cost	Estimates by agency staff
Replacement operator training	Training for new operators to replace operators who have taken permanent leave as result of accident	Transit agency--time cost	Estimates by agency staff
Misc staff support	Other staff time: employee assistance program, requests for information from public	Transit agency--time cost	Estimates by agency staff
Emergency response	Response to accident by police, fire, and medical transport	Society (local government)	Response from agency records; response costs from *(6)* or estimated
Injury costs	Costs associated with injuries incurred	Society	Injury level from accident records; costs per injury from *(6)*
Property damage	Vehicle & other property damage to other party	Society	Costs per vehicle, by injury level, from *(6)*
Rider delay	Delay to light rail system users due to accident	Society	Agency records of system delay and ridership
Road travel delay	Delay to road users	Society	From *(6)*, according to cross-street classification

* Subtracted from societal costs

** Subtracted from agency costs

pool could be reduced by reducing the number of collision accidents. Although each operator is guaranteed a standard number of hours of pay, it is possible, given a shortage of extraboard operators, that an operator may need to work overtime. The agency incurs additional expenses for overtime, which is compensated at 1.5 times the hourly wage rate. Records of overtime on a per-accident basis were not available, but the agency estimates that no more than 2 hr are accrued for a typical accident.

Supplemental Service

If both tracks are blocked for a long period of time, supplemental service such as a bus bridge or van shuttle must be provided to transport passengers to their destinations. To provide a bus bridge, an extraboard operator may be used, a deadhead may be available, or a bus may be diverted from an existing route. Although the last option may incur additional costs through rider delay on other

routes, actual examples are rare that this component was ignored. Provision of alternate service was infrequent (a bus bridge was provided in 4 percent of accidents, and some additional cases of van shuttles may not have been recorded). Data on the length or nature of such service were not available, so a crude estimate of $48 per service provision (1 hr of operator time plus overhead) was used.

Revenue Loss from Lost Riders

A loss of riders due to accident delay could occur either immediately or over the long term. For this study, the immediate loss of fare-paying riders was assumed to be negligible; the vast majority of accidents caused system delays of 15 to 20 min or less, and it was assumed that this would not be enough time to drive a significant number of riders away. (Even if a significant number of riders found alternative transportation, the one-time revenue loss would be small compared with other accident costs.)

To look at long-term effects on ridership, a time-series regression model of ridership was constructed. A regression model was used to relate dependent variables that may impact ridership to monthly ridership levels from 1987 through 1993. Accidents were incorporated in a number of ways, including gross accidents per month, injury and noninjury accidents, and delay caused by accidents. No significant relationship between accidents and ridership was found; therefore, the cost of lost ridership was assumed to be zero for this study.

Catastrophic Insurance

SCCTA is self-insured against everything but catastrophic claims (over $5 million) and severe agency property damage (over $200,000). Purchasing commercial insurance only for catastrophic situations is a practice common to most transit agencies (*1*). Although SCCTA's light rail division has never had a claim approaching the $5 million limit, insurance costs are still fairly significant: $25,000 in 1993, or over $500 when allocated on a per-incident basis. The extent to which costs could be reduced through a reduction in accidents, however, is not clear. Previous research (*1*) has found that there is some effort to account for risk when setting insurance rates, but in a highly intuitive, negotiated manner.

SCCTA purchases insurance with 10 to 12 other counties; light rail accidents, therefore, are a very small percentage of the total accidents that occur in this pool of transit agencies. Rates for the TA have declined in recent years because of a good safety record with no large losses. According to TA insurance staff the rate depends primarily on the past history and forecast probability of large accident claims, rather than the total number of accidents. Although the likelihood of a severe accident occurring is certainly related to the total number of accidents, the insurance agency does not appear to explicitly evaluate this relationship when setting rates. Therefore, it is assumed for this study that a simple reduction in the number of light rail accidents would not lead to a corresponding reduction in insurance expenses, and insurance is not included in the per-accident cost tabulation.

Agency Staff Time

Accident Response, Reporting, and Investigation

When an accident occurs, central control is called, and one or more supervisors respond to the scene; both a supervisor and the operator fill out an accident report. The supervisor then files the information, and reports are reviewed regularly by an accident review committee. In addition, a report must be filed with the California Public Utilities Commission. The light rail division estimates that a total of 2.5 to 3 hr of supervisor staff time is spent responding to accidents and processing reports. In addition, operators are paid 0.5 hr overtime for filling out a report. Reporting and investigation times appear to increase greatly in the event of a severe or fatal accident; a conservative estimate of 8 hr was used in this study. To monetize time costs, annual salaries were computed on an hourly basis and were multiplied by 2.6 (based on standard agency practices) to account for fringe benefits and overhead.

Training of Replacement Operators

In rare cases, an operator may take permanent leave because of severe psychological trauma after an accident. This has happened once at SCCTA. If so, the operator must be replaced, and retraining costs are accrued. The light rail division estimates that roughly 128 hr of staff time and 5 weeks of operator time are involved in training the operator, for a total time-cost of $9,700. If no new operator is available, additional overtime expenses will be accrued instead. In addition, after severe or fatal accidents, operators are given 1 to 2 days leave to recover from the psychological effects of an accident. This may cause a shortage of operators and the accrual of more overtime. Specific data were unavailable, so this absence was valued at 1.5 days at the standard wage rate.

Other Staff Support

The most significant additional portion of agency staff time was in the county's insurance division. Staff time spent on transit incidents was estimated at 90 percent of a full-time staff person plus 45 percent of a clerical support person. Ten percent of this time was estimated to involve light rail incidents, of which half were collision accidents. Total cost was estimated to be $248 per accident, based on the total number of accidents for 1991 through 1993.

Other staff costs are relatively minor. The TA operates an Employee Assistance Program (EAP), which offers counseling or other aid to operators who have suffered stress. The program costs $16,180 annually; the transit agency estimates that 1 percent of program time is related to light rail collision accidents. Allocating costs to injury accidents only, the cost would be $22 per injury accident.

SCCTA has not incurred any exceptional public relations expenses because of light rail accidents, but the agency does have a Public Information Officer who may respond to inquiries about accidents. The agency estimates a 3 percent response time to accidents; given a 7.5 percent allocation of accidents to light rail, a negligible per-accident cost of $15 may be assumed. In the case of a catastrophic accident it may be necessary for a transit agency to incur additional public relations costs. This is an area for further investigation.

Other Societal Costs

Emergency Response

Emergency response may take the form of the local police department, fire department, or medical transport. In addition, SCCTA

contracts with the sheriff's department to provide protective services for the division. Police, sheriff, and ambulance response were noted on the accident report forms. Fire department response was found in agency records.

Fire department and ambulance response costs were taken from *The Cost of Highway Crashes*. The average fire department response cost $550 in 1987 dollars (*6*); ambulance response averaged $221 for hospitalized cases and $167 for nonhospitalized cases, in 1992 dollars (T. Miller personal communication, 1994). The proportion of hospitalized versus nonhospitalized cases was not known from accident records, so a round figure of $200 was used. Typical police and sheriff response costs were estimated using a total response/processing time of 1 hr for police and 0.5 hr for sheriff. Personnel costs of $68 per hour were assumed, based on payroll size and employment figures for police departments, adjusted for California wage differentials and for fringe benefits and overhead (*10*).

Injury-Related Costs

Because of the limited scope of the study and privacy concerns, no attempt was made to estimate actual accident- or injury-related costs to private parties. Instead, national estimates of per-injury costs according to KABCO injury severity were taken from *The Cost of Highway Crashes* (Table 2). KABCO is the injury coding scale most commonly used by police departments in accident reporting. The scale is K = killed; A = incapacitating injury; B = evident, nonincapacitating injury; C = claimed injury; O = no injury. The limitations of the KABCO system in describing injury severity and relating to actual cost are discussed elsewhere (*6*). However, a lack of better information about the nature and severity of injuries prevented the use of a more refined injury scale.

Injury-related cost categories include hospitalization and other medical expenses; vocational rehabilitation; household production; lost wages; insurance administration; "workplace" costs including lost productivity and retraining; emergency services; legal/court costs; and pain and suffering. On a case-by-case basis, actual costs will differ considerably from average cost estimates. The study assumes, however, that on the average costs according to injury level are the same as those estimated nationally from highway crash data.

Most categories were applied directly, based on the number and severity of injuries in each accident. However, some categories had to be adjusted because of the unique nature of the study. Emergency services were eliminated, having already been estimated on a per-response basis. Legal expenses were adjusted, because it appears that light rail accidents are less likely to involve court proceedings and legal expenses than the typical highway accident. The vast majority of attorneys are reimbursed as a percentage of the settlement won, 29.4 percent on the average. Court costs and fees average another 2 percent (*11*). Therefore, other-party legal expenses were estimated by taking 31 percent of compensation paid by the transit agency to other parties. This probably underestimates actual legal expenses because in some cases parties may sue their own insurance company or contact an attorney without going to court. Insurance administration costs were not adjusted and may slightly overestimate actual costs because the light rail agency's administration costs are already included. Per-injury insurance administration estimates are based on the costs eligible for compensation, medical, lost wages and household production, and property damage, and published administrative expense ratios (*6*).

Pain and suffering are a large component of comprehensive injury costs. Estimates are based on numerous studies of willingness to pay to reduce risk (for example, the amount that automobile consumers are willing to pay for airbags or other safety-related features). Pain and suffering costs should not be ignored as part of the overall cost to society, even though their measurement is imprecise. Studies of willingness to invest in safety at a personal level should be directly applicable to the determination of societal levels of safety investment.

Property Damage to Private Vehicles

Property damage to private vehicles was also taken from *The Cost of Highway Crashes*, with cost estimates on a per-vehicle basis according to injury level. Damage estimates of "minimal," "moderate," and "major" were available from accident reports, but the correspondence of these levels to actual cost is unknown. However, an analysis of the correlation of injury level to reported damage level did show a significant positive relationship within the accident data set, so it seems reasonable to base property damage costs on injury level. Again, on a case-by-case basis, costs will differ markedly. A property damage cost of $150 was assumed for bicycle accidents.

Rider Delay

To estimate rider delay, train-minutes of delay were taken from agency records and were multiplied by estimates of the number of riders affected, based on agency ridership surveys by time of day and location. Delay is probably overestimated because the delay of two consecutive trains would actually result in many riders catching the first train instead of the second train. Nevertheless, the estimates of 29.1 passenger-hr for a noninjury accident and 80.3 passenger-hr for an injury accident should serve as a reasonable approximation. Delay time was valued for passengers at 67.5 percent of the average national wage rate (*6*), adjusted for California

TABLE 2 Costs per Injury by KABCO Severity (1988 Dollars)

Injury Level	Hosp/ Med	Voc Rehab	Household Production	Wages	Insurance Admin	Workplace	Pain & Suffering
K	$5,859	$0	$92,014	$428,316	$43,751	$6,186	$1,743,917
A	$9,660	$69	$3,250	$11,728	$2,470	$961	$133,925
B	$1,742	$24	$845	$2,946	$721	$333	$22,858
C	$1,017	$19	$522	$1,782	$484	$223	$9,927
O-Per Vehicle	$73	$1	$71	$135	$155	$45	$369

Source: Miller et al, 1988

wage differentials, with wage information from the U.S. Bureau of Census (*10*).

Road Travel Delay

The Cost of Highway Crashes gives crude figures for road travel delay, estimated from simulations, for highway accidents. Estimates are provided for freeways, arterials, and collector streets. For this analysis, these delay estimates are applied based on the classification of the cross-street where the accident occurred. Delay is valued at 90 percent of the wage rate for drivers and 67.5 percent for passengers (*6*). (The differential between driver and passenger delay values reflects the greater disutility of time spent driving compared with time spent riding in a vehicle.) Again, this should only be considered a first approximation, and actual delay values may vary considerably.

RESULTS

Estimated Costs

A breakdown of average costs by agency and nonagency categories and by accident severity is given in Table 3. Costs by cost category are given in more detail in Table 4. Direct and indirect costs to the transit agency averaged $2,568 overall, including $1,872 for a noninjury accident and $3,972 for an injury accident. Additional costs to society, including pain and suffering, totalled $7,238 for each noninjury accident and $202,439 for each injury accident.

Overall, the most substantial component of agency costs was vehicle damage ($3,915 per accident), followed by claims administration ($1,174) and legal costs ($874). On average, however, $4,311 of the agency's total costs were recouped from the other party involved in the accident. Legal costs and claims paid tended to be infrequent (less than 10 percent of all accidents) but relatively large, averaging $9,161 and $2,969, respectively, in cases in which they did occur. Catastrophic insurance was also a relatively substantial cost when calculated on a per-accident basis ($660 in 1993), but it is not clear that a reduction in accidents would lead to a near-term reduction in insurance costs, so this was not included in the total cost estimate. Agency staff time and driver overtime costs were smaller but still substantial, at $560 per accident. Costs were not substantially greater for minor injury than for noninjury accidents. Also, no measurable long-term impact on ridership was found.

For costs not borne by the agency, emergency response, rider delay, and road user delay costs were a relatively minor component except in property damage-only accidents. Emergency response costs averaged $163 per accident; rider delay averaged 63.5 passenger-hr or $548. Again, a few cases of unusually high delay skewed the average somewhat.

Reliability of Estimates

Detailed agency cost data were available for 53 noninjury and 23 injury accidents. The costs for noninjury accidents were relatively consistent, and therefore the estimates for property damage-only accidents may be considered fairly reliable. The cost per injury accident, however, could be highly influenced by just one or two large claims, on the order of hundreds of thousands or even millions of dollars, which may occur once every few years. No claims over $16,000 were paid by the agency in the 3.5-year time period for which records were available, but one $300,000 claim (not included in the data set) was recorded in the first 3 years of the system's operation. If this $300,000 claim payment had occurred in the period covered by the data set, average agency costs would have increased from $2,870 to $6,544 per accident. Claims payments would have comprised 40 percent of agency costs rather than 6 percent. Therefore, the cost estimates for injury accidents should be regarded as less reliable because of the more variable nature of the data. It should also be noted that claims cases can sometimes take many years to resolve, so it is possible that costs have been underestimated for the existing data set.

TABLE 3 Average Cost per Accident and by Accident Severity

a Average Cost Per Accident (1993 dollars)

Transit Agency	$2,568
Non-Agency	
Direct	$22,817
Pain & Suffering	$49,096
Total Societal	$74,481

b Average Cost by Accident Severity

Injury/Fatality		Property Damage Only	
Transit Agency	$3,972	Transit Agency	$1,872
Non-Agency		Non-Agency	
Direct	$55,171	Direct	$6,786
Pain & Suffering	$147,268	Pain & Suffering	$452
Total Societal	$206,411	Total Societal	$9,111

TABLE 4 Average Cost by Cost Category and Accident Severity (1993 Dollars)

Cost Category	All Accidents	Injury/ Fatality	PDO
Total Accidents	166	55	111
Transit Agency			
Direct--Per Accident			
Property Damage	$3,915	$2,657	$4,538
Claims Processing	$1,174	$1,609	$959
Claims Payments	$320	$800	$83
Claims Received*	($4,311)	($4,311)	($4,311)
Legal & Court Expenses	$874	$2,428	$104
Operator Overtime	$75	$89	$69
Supplementary Service	$2	$4	$0
Revenue Loss	$0	$0	$0
Direct--Annual			
Catastrophic Insurance**	$0	$0	$0
Indirect--Staff Time			
Accident Response, Reporting & Investigation	$191	$215	$179
Replacement Operator Training	$58	$176	$0
Misc. Staff Support	$269	$284	$262
Non-Agency			
Emergency Response	$154	$241	$111
Property Damage	$1,780	$2,463	$1,442
Injury-Related Costs			
Medical, Lost Production, Legal, etc.	$16,368	$48,161	$614
Pain & Suffering	$49,096	$147,268	$452
Delay			
Rider Delay	$397	$692	$251
Road Travel Delay	$128	$123	$130
Transfer Payments			
Claims to TA*	$4,311	$4,311	$4,311
Claims received from TA	($320)	($800)	($83)
Total Societal Cost	$74,481	$206,411	$9,111

* Breakdown by injury vs. non-injury not available
** Cost not allocated on a per-accident basis

Costs by Accident Type

Costs were also broken down by accident type (Table 5). Accidents were classified as "left-turn" (parallel-running vehicle turns left in front of the light rail vehicle (LRV)); "right-angle" (motor vehicle pulls out from a side street); "motor vehicle-other" (including mostly right-turn and anti-parallel, left-turn accidents), and "pedestrian/bicycle." Differences by agency cost category, including LRV damage, claims administration, claims payments, and legal expenses, were tested for significance using a Tukey studentized range test on the variable means. LRV damage and total itemized costs were significantly greater for right-angle accidents than for other types, and claims processing and legal expenses were significantly greater for pedestrian and bicycle accidents, due to the greater probability of injury in such accidents.

Costs for most other categories were defined based on injury severity, and differences in costs among accident types should be caused primarily by differences in the proportion of injuries sustained for each type. A significance test on total nonagency costs showed that costs were substantially higher for pedestrian and bicycle accidents, again due to the greater probability of injury. Differences among accident types involving motor vehicles were insignificant.

Transferability of Results

Although the cost methodology developed is generally applicable, the usefulness of the actual numbers is limited because actual data were taken from only one transit property. When considering costs to other light rail transit properties, both geographical differences in wage rates, legal costs, and so on and differences in operating procedures, equipment, and system characteristics may lead to different costs among properties.

TABLE 5 Cost by Accident Type (1993 dollars)

	1 Left-Turn	2 Right-Angle	3 Other M. V.	4 Ped/Bicycle	Total (Motor Veh.)	Total (All Accidents)		
Total Number	106	14	27	16	147	163		
Total W/Itemized Costs	44	8	16	8	68	76		
Transit Agency -- Itemized								
Property Damage	$3,017	$16,995	$1,094	$408	$4,472	$3,915	**	2 sdt 1,3,4[a]
Claims Processing	$1,016	$1,259	$987	$2,191	$1,038	$1,174	**	4 sdt 1,3
Claims Payments	$210	$0	$0	$2,016	$136	$320	*	4 sdt 1,2,3
Legal & Court Expenses	$309	$771	$381	$5,201	$380	$874	**	4 sdt 1,3
Total Itemized	$4,552	$19,025	$2,462	$9,816	$6,026	$6,283	**	2 sdt 1,3
Total Agency[b]	--	--	--	--	--	$2,568		
Non-Agency								
Direct	$10,138	$13,227	$8,990	$142,034	$10,221	$22,817	**	4 sdt 1,2,3
Pain & Suffering	$9,561	$18,626	$6,305	$419,006	$9,827	$49,096	**	4 sdt 1,2,3
Total Societal	$21,558	$40,677	$16,065	$565,839	$22,370	$74,481	**	4 sdt 1,2,3

* = F-test for difference of means significant at 0.10 level

** = F-test for difference of means significant at 0.05 level

[a] read as "cost for type 2 (right-angle) accident is significantly different than for type 1, 3, or 4"

[b] Data unavailable by accident type. Total is less than "Total Itemized" due to claims received.

In general, highway accident costs tend to be slightly higher in California than for the nation as a whole; costs in Santa Clara County seem to be close to the statewide average. The statewide cost per claim in 1989 was $8,187 for bodily injury claims and $1,638 for property damage claims, compared with a nationwide average of $7,950 and $1,380, respectively (this average excludes states with no-fault insurance) (*12*). Pain and suffering, the greatest component of full societal cost, accounted for 27 percent of bodily injury awards in Santa Clara County, also roughly the statewide average. Although the propensity to award compensation for pain and suffering varies across regions, in general it is treated as a multiple of tangible costs and therefore increases proportionally as medical and other costs increase (*13*).

Overall, costs in Santa Clara County would be expected to be higher than average because of a number of factors. Compared with the national average, wage costs are 11 percent greater in California and 22 percent greater in Santa Clara County (*10*). Differences in the insured vehicle fleet, such as a greater proportion of small and urban-garaged vehicles, also lead to higher-than-average claims losses (*14*). Therefore, agency-related costs for the SCCTA should be higher than for a light rail system located in an area of average wage rates and accident claim costs. Note that most nonagency costs are already based on national averages.

Costs to the TA could also be affected by the proportion of uninsured motorists in the region, which would affect the agency's ability to recover costs from the motorist. In 1990 the proportion of uninsured motorists was estimated to be 20 to 25 percent for the state as a whole and 15 to 20 percent for the San Francisco Bay area (*15*). In urban areas where the proportion of uninsured motorists is higher, the TA would be expected to recover a smaller portion of its costs.

Another source of cost variation among properties would be differences in the proportions of accidents involving injuries, severe injuries, and deaths. System characteristics, particularly operating speed, are a primary determinant of accident severity. A logit severity model, based on data from the light rail systems in Santa Clara County and San Francisco, showed (as expected) that the probability of an accident resulting in injury increased significantly as the speed of the light rail vehicle increased. "Left turn" accidents were also found to have a higher probability of injury than other accident types, as did accidents that occurred during the morning and evening peak hours. (Left turn accidents were not significantly more severe for the Santa Clara data set alone.) Therefore, systems that operate at speeds upward of 40 or 45 mph through grade crossings would tend to have more frequent and severe injuries, and therefore higher accident costs, than the Santa Clara system, which operates at a maximum of 35 mph. Severity may also depend on other system characteristics, such as the configuration of grade crossings.

POLICY IMPLICATIONS

Significance of Severity

As demonstrated in the crash cost literature referenced in this paper, total societal costs are highly dependent on the severity of injuries in the accident. A fatality can have costs an order of magnitude greater than an incapacitating injury, which may in turn have costs an order of magnitude greater than a minor injury. In the case of a transit agency's costs, another dimension enters the picture: the probability that the agency will be found partially or fully responsible for an accident. Because of a widespread emphasis on safe sys-

tem design and operating procedures and the limited potential for driver error on a rail transit system, this probability seems quite low for the new light rail transit properties. It is certainly nonnegligible, however, and even a single severe or fatal accident can result in liability claims in the hundreds of thousands of dollars, 10 to 100 times the cost for a "typical" accident. The fact that the agency has "deep pockets" may add to the likelihood that it is sued in the event of a severe accident. Transit agencies realize this and set aside a substantial pool of money for self-insurance purposes in addition to carrying outside catastrophic insurance. Overall, the implication is that any measures a transit agency can take to protect itself from liability could have potentially significant payoffs.

Qualitative evidence also shows that other costs increase substantially in the case of a severe accident. Agency staff spend many hours responding to the accident and conducting follow-up investigations. A lengthy police report is filled out and, in the case of a fatality, the California Public Utilities Commission (PUC) sends an investigator to the scene of the crash. In extreme cases, an operator may need to take extended leave, resulting in personnel shortages or retraining costs. Finally, severe accidents can also have disproportionate effects on public perceptions of safety. Cheaney et al. (*1*) note that society displays a degree of tolerance for noncatastrophic accidents but may react strongly to accidents they perceive as "catastrophic."

Overall, reducing the severity of accidents may be even more productive than reducing the absolute number of accidents. For example, earlier detection of a potential accident could allow a greater reduction in LRV speed before impact, thereby reducing the probability of injury. The expected cost reduction could then be calculated. The results of the cost severity analysis may also be useful in narrowing the focus of countermeasure implementation. Although the total number of pedestrian and bicycle accidents was small (10 percent of all accidents), this category was particularly expensive; the probability of the accident resulting in injury was almost 60 percent, and all three fatalities were in this category. Therefore, efforts to reduce pedestrian accidents may have significantly larger payoffs on a per-accident basis than efforts to reduce vehicle accidents. Conversely, right-turn accidents on the downtown pedestrian mall, where operating speeds are low, rarely resulted in injury or substantial property damage and may deserve relatively little attention.

Implications for Safety Investment

A transit agency acting in its own economic self-interest may be expected to invest in safety improvements up to the point where the costs of such improvements equal the benefits to the agency. However, investment beyond this point can still achieve significant societal benefits that do not accrue to the transit agency. This becomes more true as the severity of the accident increases because most injury-related costs (by far the largest component of injury accident costs) are not borne by the transit agency. For the data set analyzed the net cost paid by the transit agency was a very small proportion of the total accident cost.

Although the potential for liability is an incentive for transit agencies to make larger safety investments, it does not increase the monetary risk to the level of full societal costs, particularly because the light rail agency is rarely found at fault. The disparity between costs to the transit agency and costs to society suggests that safety investment decisions should be made at the societal level rather than at the level of one particular agency. Legislators, for example, may wish to fund safety investment programs independently of the transportation agency's operating budget. As mentioned earlier, the full societal cost of an accident represents the maximum rational public expenditure to prevent such an accident (*6*). In the likely event that safety programs are funded at a lower level, legislatures might conduct an explicit comparison of the cost-effectiveness of various safety improvement programs across both transportation and nontransportation areas. Such a comparison would help society achieve the maximum benefit (in terms of accidents, injuries, and deaths prevented) per dollar spent.

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REFERENCES

1. Cheaney, E. S., J. A. Hoess, R. E. Thompson, and R. L. Svehla. *Safety in Urban Mass Transportation: Research Report.* Batelle, Columbus Laboratories, Urban Mass Transit Association, U.S. Department of Transportation, 1976.
2. FHWA. *Railroad-Highway Grade Crossing Handbook.* U.S. Department of Transportation, 1986.
3. Office of the President. *Principles of Federal Infrastructure Investments.* Executive Order 12893. Washington, D.C., 1993.
4. National Safety Council. *Accident Facts, 1993 Edition.* Itasca, Ill., 1994.
5. NHTSA. *The Economic Cost to Society of Motor Vehicle Accidents, 1986 Addendum.* NHTSA, Washington, D.C., 1987.
6. Miller, T., J. Viner, S. Rossman, N. Pirdus, W. Gellert, J. Douglass, A. Dillingham, and G. Blomquist. *The Cost of Highway Crashes.* FHWA-RD-91-055. FWHA/The Urban Institute, U.S. Department of Transportation, 1991.
7. Jones, G. D., L. B. Keys, M. Y. LeBlanc, A. J. Warshawer, and M. Wallace. *Development of a Safety Program Plan for the Office of Safety and Qualification.* University of Southern California/Institute of Safety and Systems Management, Los Angeles, Calif., 1977.
8. FTA. Section 15 Data Tables for Report Years 1987–1992. FTA, U.S. Department of Transportation, 1988–1993.
9. Walmsley, D. A. *Light Rail Accidents in Europe and North America.* U.K. Transport and Road Research Laboratory Report #335. U.K. Transport and Road Research Laboratory, Crawthorne, Berkshire, 1992.
10. U.S. Bureau of the Census. *Statistical Abstract of the U.S., 1993*, 113th ed. Washington, D.C., 1993.
11. All-Industry Research Advisory Council (AIRAC). *Attorney Involvement in Automobile Injury Claims*, 1988.
12. Insurance Research Council. *Trends in Auto Bodily Injury Claims.* Oak Brook, Ill, 1990.
13. California Department of Insurance. *Automobile Claims: A Study of Closed-Claim Payment Patterns in California.* Sacramento, Calif., 1993.
14. Highway Loss Data Institute. *Automobile Insurance Losses: A Comparison of California and National Results.* Washington, D.C., May 1988.
15. Marowitz, L. *Uninsured Motorists: Their Rate and Cost to Insured Motorists.* Final Report to Legislature of State of California, California Department of Motor Vehicles, Sacramento, Calif., December 1991.

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