PARAMETRIC ANALYSIS OF DUAL-MODE TRANSIT: PRELIMINARY CASE STUDY

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Greater understanding of the impact of different transit service configurations on system costs and benefits is needed, particularly in relation to new technologies. The purpose of this paper is to demonstrate a method for analyzing service trade-offs. Through a case study conducted in Milwaukee, the paper examines the sensitivity of four service characteristics for dual-mode transit, one of several promising technological innovations. The four service characteristics are main line speed, guideway spacing, vehicle size, and station spacing. Preliminary comparative analyses of these four features are conducted, in relation to nine output or system performance variables: annual operating costs, annual capital costs, total annual costs, average travel time, estimated ridership, required fares (operating costs), required fares (all costs), annual transport benefits, and benefit-cost ratio. Graphical techniques are explored for highlighting comparative sensitivities. The need to systematically examine different combinations of service features within different urban areas is stressed.

•AS increasing attention is given to the potentials for various innovative urban transit technologies, interest has grown in the relative importance of the different service parameters that such technologies offer. For example, several studies of the sensitivity of systems performance and desirability to various service parameters for dial-a-bus (1), multipurpose activity center systems (2), conventional bus transit (3), and dual-mode transit systems (4) have recently been completed. A general study of parametric service variations for generic urban transit systems has also been conducted (5), dealing with five different versions of a hypothetical, relatively extensive automated guideway transit system.

The notion of more carefully examining various combinations of service characteristics, in order to define and systematically characterize alternative transit systems, also seems to be influencing urban transit planning itself. For example, in a recent paper, it was observed that systematic choices of transport technologies will require that techniques for identifying subsystem trade-offs and local cost or performance optima be developed (6). In another example, a service specification model has been developed for screening candidate packages of service characteristics. The model converts the specific hardware characteristics and operating methods of any candidate system into a set of performance and user impacts (7). In a third example, a successive-approximations approach was used in the sensitivity analysis of alternative feeder and local transit systems in a suburban portion of the San Francisco BART service area. Under this approach, emphasis is placed on the early though approximate analysis of a wide range of service configurations to ensure that all reasonable alternatives receive adequate attention. Four successive and increasingly detailed rounds of analysis were conducted, with each round considering only the most promising configurations resulting from the previous rounds (8).

This paper presents an extension of the sensitivity analyses of dual-mode transit conducted in the study cited previously. It offers a framework for the sensitivity analysis

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of any area-wide express transit system, permitting direct trade-offs to be made among different service parameters. These trade-offs are expressed in terms of costs, performance levels, required fares, and transport-related benefits. Although many possible service parameters could be studied, four service characteristics that appear to be especially important are used to demonstrate the analytic approach. It is acknowledged that many other service parameters should also receive careful study. Some service characteristics, such as the maximum pickup time or the shape of the service area for dial-a-bus, or guideway configuration or vehicle headways for MAC systems, are more specialized in nature and deal with only a portion of metropolitan-wide urban transit systems.

Emphasis in the dual-mode transit sensitivity analysis was placed on service parameters derived from a simulation of peak-hour, door-to-door travel characteristics across the entire urban area. The four basic service characteristics studied—guideway spacing or guideway resolution (total miles of guideway within the fixed service area), station spacing (average distance between stations), vehicle size (number of passengers per bus), and main line speed (in mph)—appear to represent the most critical aspects of express urban transit service influencing attractiveness and ridership levels. These four variables then are the focus of this analysis and provide the inputs for the case study sensitivity evaluation.

Figure 1 shows the nine output characteristics of express transit service that were examined as a function of these service parameters.

CASE STUDY ASSUMPTIONS AND RESULTS

The dual-mode transit case study conducted in Milwaukee County involved the delineation of a hypothetical 110-mile, eight-corridor guideway network; a ridership forecast based on travel time and quality-of-service characteristics; a transit network assignment to determine system operating and performance characteristics; detailed operating and capital cost analyses; and preliminary analyses of transport and community impacts and benefits. Access to the hypothetical guideway system was provided at 40 different stations. Downtown distribution was accomplished via two separate downtown guideway tunnels, with six additional stations located along each tunnel. A constant speed of 55 mph along the main line guideway was assumed (with off-line acceleration and deceleration), together with an average operating speed in the downtown area of 13.5 mph (including time for station stops). An average of 6.6 neighborhood transit collection routes, conducted under manual driver operation, would emanate from each of the 40 outlying guideway access points (9, 10).

The equations and assumptions employed in the case study sensitivity analysis are defined in more detail in the Appendix. In general, these equations have been derived from data established for the peak-hour conditions of the case study system (e.g., ~ 110 miles of guideway, ~ 2,600 vehicles, ~40 stations, 55 mph, etc.). In some cases the relations examined are linear, and in other instances they are approximated by a few straight-line segments or a simple curve fit. Because each equation is based on simplifying assumptions, it must be recognized that the greater the departure of a given service characteristic from the design or simulated condition, the less likely or credible the result becomes.

Transport Supply

As noted previously, transport supply is represented in this analysis by four system output characteristics: annual operating costs, annual capital costs, total annual costs, and total travel time for the average trip. The impact of each of the four service characteristics (which, in a sense, could themselves be considered to be supply characteristics) on each of these output features will depend on a variety of unit costs and travel time components. Some costs and travel time segments will remain fixed, regardless of any change in a particular service characteristic. This section describes the assumptions and resulting equations from which the parametric curves presented later have been derived. (Total annual cost curves represent a linear combination of operating and capital cost curves and are not discussed further.)

Equations developed to estimate relative impact on operating costs, capital costs, and average travel time, for each of the four service characteristics, are shown in the Appendix (Tables 3, 5, 7, and 9). Accompanying each of these is a separate table (Tables 4, 6, 8, and 10) listing the assumptions on which each equation is based. These assumptions detail many of the results of the case study simulation, particularly in the areas of cost analysis, ridership forecasting, and transit network assignment.

These equations are illustrative only and should not be taken out of context. They suggest only how critical cost and travel time components can be singled out for analysis and how assumptions regarding their variability with various service characteristics must be made. Further studies of these variabilities appear warranted, especially as changes in service characteristics become more extreme. In general, halving and doubling of each service characteristic were taken as the range of interest. All equations and relations are consistently expressed in terms of proportional variations from simulated values (that is, as proportional multipliers of from 0.5 to 2.0). This form of normalization allows the efficiency or effectiveness of service characteristics measured in different units to be compared on a single scale.

The general form of each equation consists of (a) a constant representing those costs or portions of travel time not affected by the service variable at hand, (b) costs or travel time components that vary inversely with the service characteristic, and/or (c) costs or travel time components that vary directly. In some cases, separate technical analyses were conducted to account for additional cost variations that were over and above those resulting from the service characteristics alone. For example, annual capital costs for vehicles (Table 1), as a function of vehicle size, can vary both with the number of vehicles required (inverse relation) and with a per-unit change in cost as vehicle size changes (separate equation needed).

Transport Demand

Parametric analyses of demand can be no stronger than the mode split forecasting procedures utilized for the basic simulation. In the Milwaukee dual-mode case study, mode split was treated very simply, with subjective modifications of diversion curve (travel time ratios between highways and dual-mode transit) outputs made to reflect quality-of-service improvements. It was estimated that roughly 22 percent of daily peak-period travel would be attracted to dual-mode transit. The effects of variation in each of the four service characteristics on demand were estimated primarily through their impact on average trip travel time only. However, these previous adjustments to the diversion curve mode split, intended to reflect improved quality of service (e.g., all seated, arrival time certainty, and few transfers), were still carried forward.

A supplementary curve was derived to show the relation between travel time and ridership changes, adjusting for the comfort-convenience modifying factors. This curve was used to derive ridership impact estimates for each of the four service characteristics, according to their corresponding impact on travel time. It was found that forecasted ridership is relatively stable with regard to changes in average travel time. For example, if travel time were to increase as much as 18 percent, the system would still retain 90 percent of its estimated ridership. If travel time were to decrease 18 percent, ridership would gain only about 7 percent. Subsequent analyses also showed that, under more desirable service characteristics than those simulated, ridership would still vary only about 3 or 4 percent.

Required Fares

Consequently, in the analysis of required fares, depicted as ridership-cost ratios, the operating cost and total cost curves described earlier were utilized. Remember that these cost curves were based on fixed levels of ridership. However, further adjustments in costs due to the modest ridership changes previously mentioned would be relatively minor, and these adjustments were not made. The revenue-cost analyses were thereby simplified somewhat. They amounted to only a matching of ridership changes against associated cost changes for incremental fluctuations in each of the four service characteristics. No new data were introduced; rather, comparable points on the ridership and cost curves were matched and their ratios replotted.

Figure 1. General framework for sensitivity analysis.

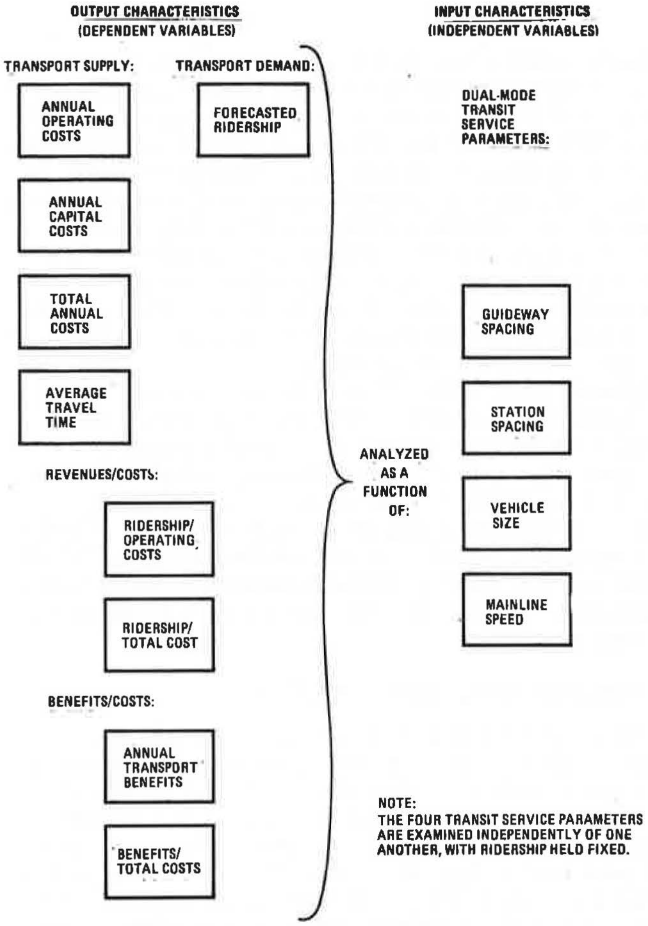

Table 1. Estimated impacts of revised service characteristics.

		Alternative Case			
		1	2	3	4
Characteristic	Reference Case[a]	Vehicle Size, 19 to 38 Passengers	Guideway Miles, 110 to 165 Miles	Station Spacing, 2.75 to 1.65 Miles	Main Line Speed, 55 to 70 mph[b]
Annual costs (thousands of dollars)					
Operating	58,251	39,086	59,590	60,056	56,270
Capital	46,040	43,047	55,754	49,171	41,160
Total	104,291	82,133	115,344	109,227	97,430
Annual ridership (thousands)	97,000	90,300	100,200	98,900	100,200
Required fares (cents)					
Operating costs	60.0	43.3	59.5	60.7	56.2
Capital costs	47.5	47.7	55.6	49.7	41.0
Total costs	107.5	91.0	115.1	110.4	97.2
Annual transport benefits (thousands of dollars)	150,773	90,467	174,334	170,675	182,909
Benefit-cost ratio[c]	1.08	0.83	1.16	1.18	1.38

Note: These are illustrative and preliminary results only and should not be applied in other contexts without considerable further study.

[a] Full-scale dual-mode transit system as originally simulated in Milwaukee County.

[b] Highest average trip speed attainable would be desirable—70 mph used for illustrative purposes.

[c] Additional accident costs and travel time losses (for choice riders) were included in calculating the benefit-cost ratio.

Transport Benefits

The impacts of service characteristic changes on total transport benefits were also included in the parametric analysis. A limited benefit-cost analysis was conducted for the case study, where it was acknowledged that the seven benefits analyzed should not be construed as the full range of impacts that might be attributed to a dual-mode guideway network. Rather, they represent only those consequences that impact directly on users of the guideway system or indirectly on those persons continuing to use the street and freeway network. The seven benefit (or disbenefit) categories covered included transit travel time savings (for captive trips), transit travel time losses (for choice trips), accident costs avoided, transit accident costs incurred, private-vehicle operating costs avoided, CBD parking costs avoided, and highway travel time savings. Changes in total transport benefits were recalculated for a sampling of travel time and resultant ridership changes for each of the four service characteristics.

This entailed an interpolation, from previous calculation of benefits for all levels of dual-mode ridership, of the following transport benefits: highway travel time savings, accident costs avoided, private-vehicle operating costs avoided, CBD parking costs avoided, and transit accident costs incurred. For the two remaining categories of transport benefits, it was necessary to recalculate transit travel time savings and transit travel time losses according to the accompanying travel time changes. Finally, travel time losses for choice riders were also adjusted to account for the ridership increment or decrement that was involved. The results of these recalculations of transport benefits were then plotted graphically, and benefit-cost curves were replotted in the same manner as were revenue-cost curves.

ANALYSIS OF COMPARATIVE SENSITIVITIES

The basic results of the case study sensitivity analyses are shown in Figures 2 through 10 and are discussed briefly in this section. As noted earlier, the general approach used in analyzing these relations has been to match a proportional change in each of the four input service characteristics against a corresponding proportional change in each of the nine output characteristics previously defined. That is, a proportional change in each service characteristic may range from 0.5 to 0 to 2.0, with 0 representing no change, 2.0 representing a 100 percent increase (or a doubling), and 0.5 representing a reduction to 50 percent of the simulated value (or a halving). Similarly, corresponding changes in output characteristics are shown on a comparable scale.

Proper interpretation of these data is given in an example that refers to Figure 2. Figure 2 shows the sensitivity of annual operating costs to variations in service characteristics. It can be seen from the figure that vehicle size has the greatest effect on annual operating costs. (Vehicle size largely determines the vehicle fleet size as well as the driver force, the two largest single operating cost items.) Let us assume that we wish to examine the effect of increasing vehicle size by 50 percent on system operating cost. Referring to Figure 2, a value of 1.5 on the abscissa (vehicle size of 19 + 9.5 = 28.5, or 29) leads to a resultant value on the ordinate scale of 0.78. Thus, an increase in vehicle size of 50 percent results in a 22 percent reduction in total annual operating costs or in this instance a reduction from $58 million to approximately $45 million.

Table 2 gives the highlights of the relations depicted in Figures 2 through 10. It identifies the service characteristics that are most sensitive, as well as those that are least sensitive, in influencing the various system output characteristics. The table is based on an examination of the relative slopes at the design point (1.0, 1.0) of the various curves shown in Figures 2 through 10.

Table 2 shows, for example, that total annual costs are most sensitive to changes in vehicle size (as indicated by the absolute value of each slope). Ridership levels, on the other hand, are most sensitive to changes in main line speed and least sensitive to changes in station spacing. Expected revenues (or ridership-total annual cost ratio) are most sensitive to main line speed, meaning that increasing vehicle guideway speed represents the most profitable way to reduce required fares (although it is least sensitive to station spacing), which indicates that decreasing or increasing station spacing will have relatively little effect on required fares. Column as well as row comparisons

Figure 2. Operating cost sensitivities.

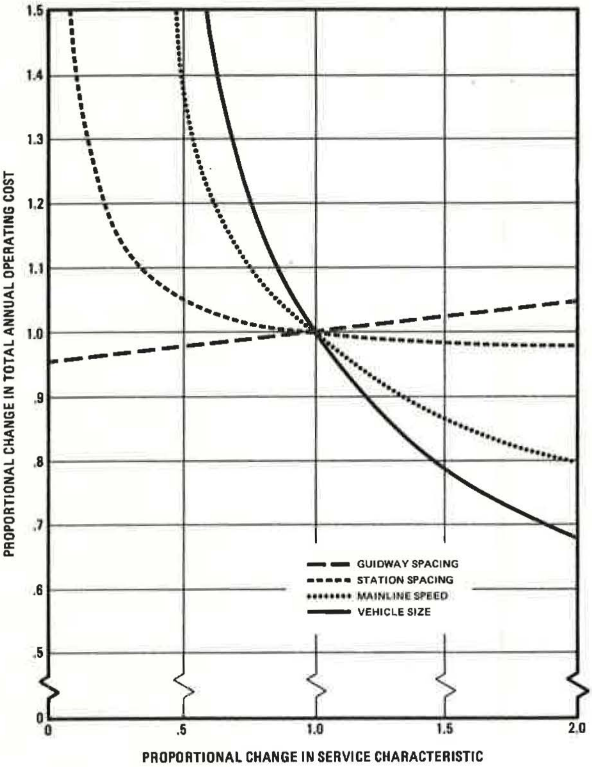

Figure 3. Capital cost sensitivities.

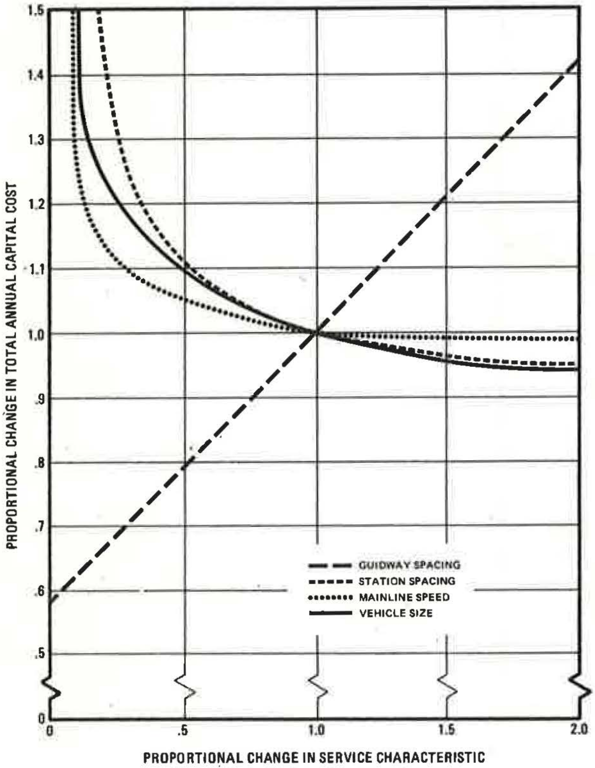

Figure 4. Total cost sensitivities.

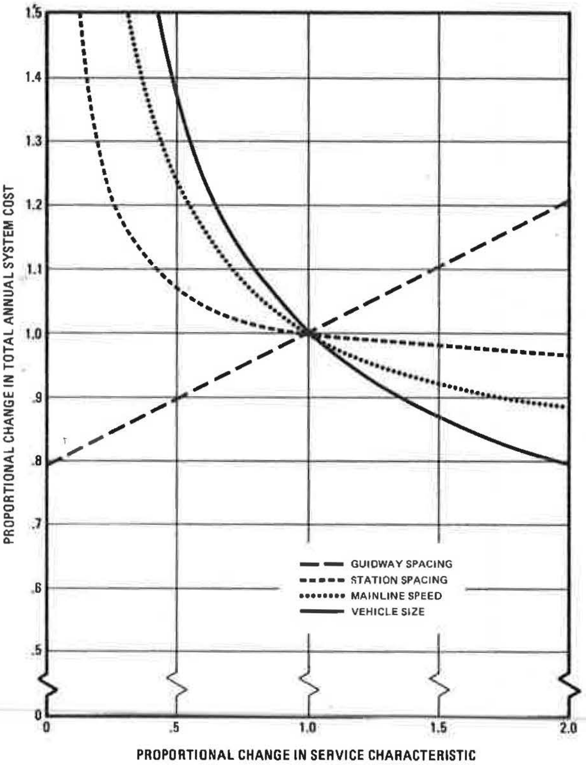

Figure 5. Travel time sensitivities.

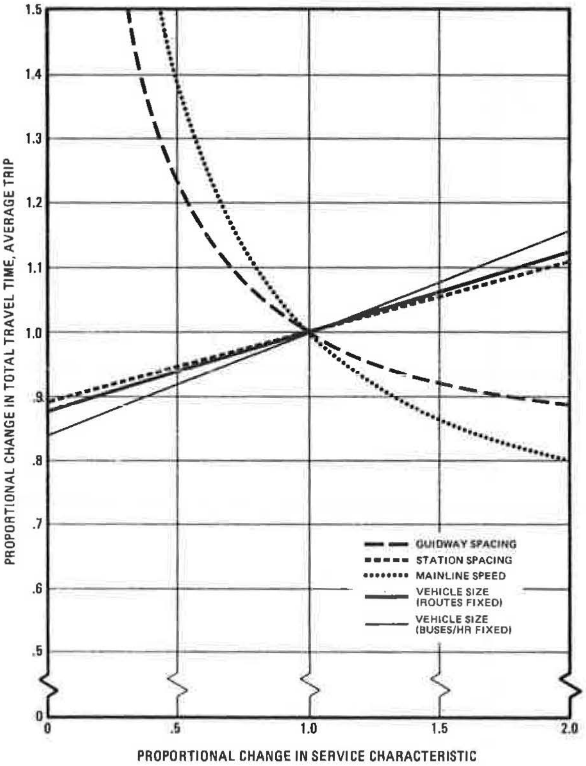

Figure 6. Ridership sensitivities.

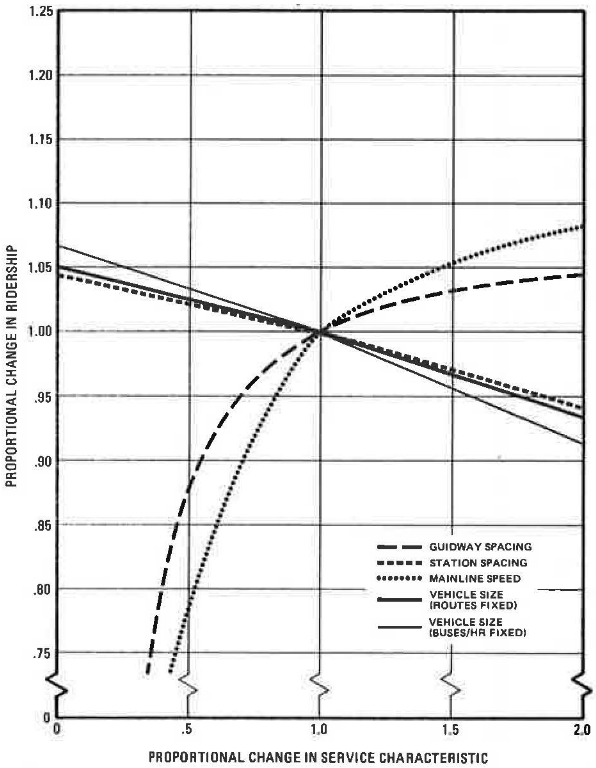

Figure 7. Operating fare sensitivities.

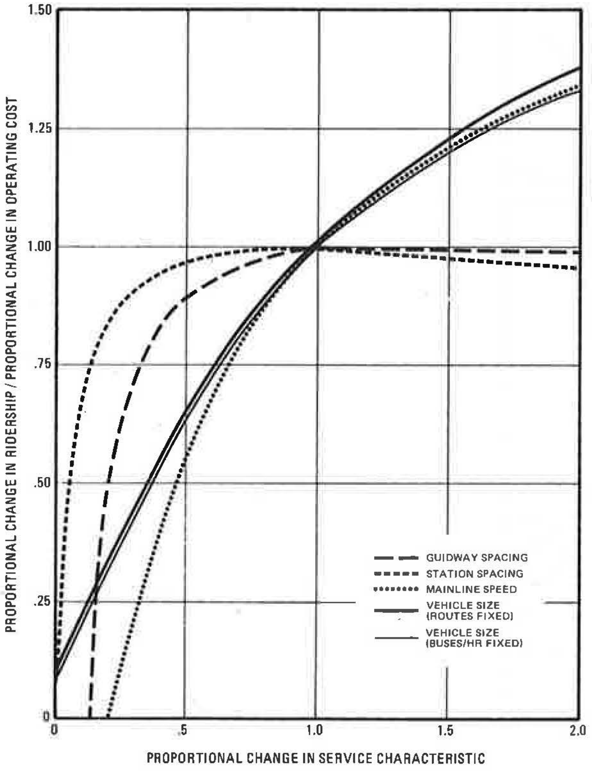

Figure 8. Overall fare sensitivities.

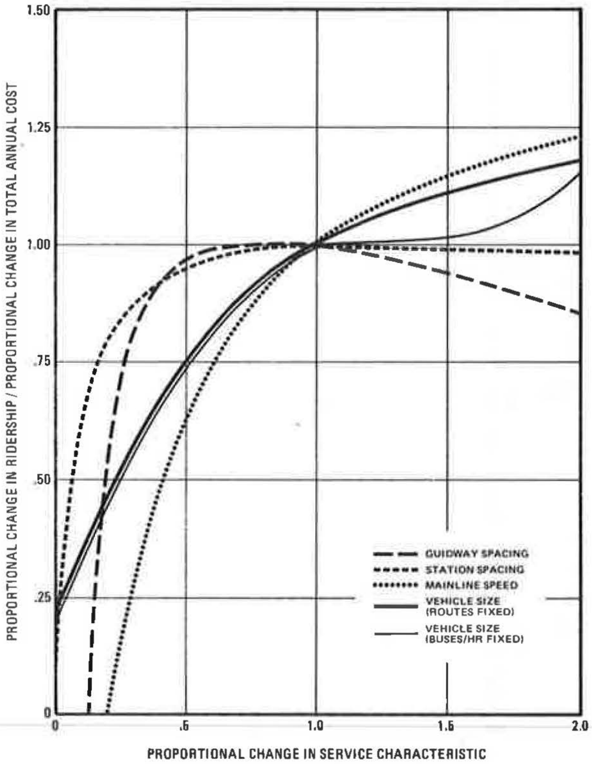

Figure 9. Transport benefit sensitivities.

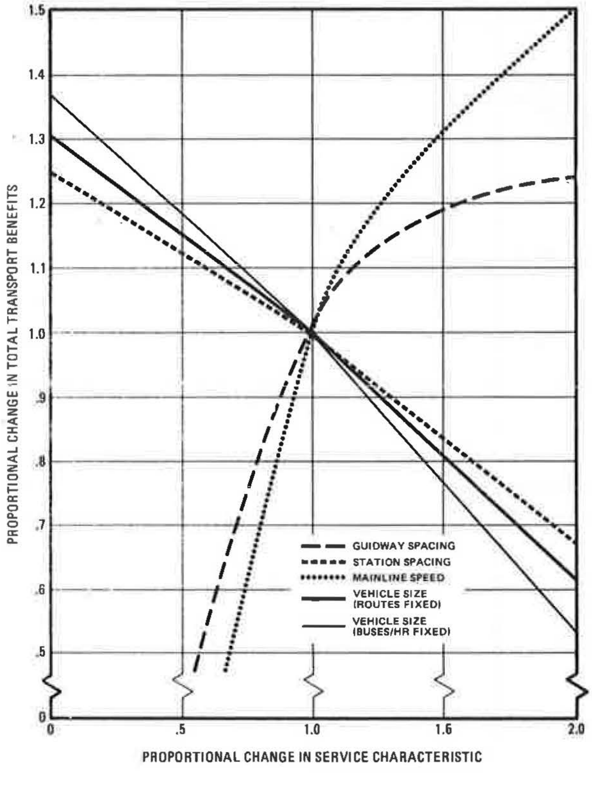

Figure 10. Benefit-cost sensitivities.

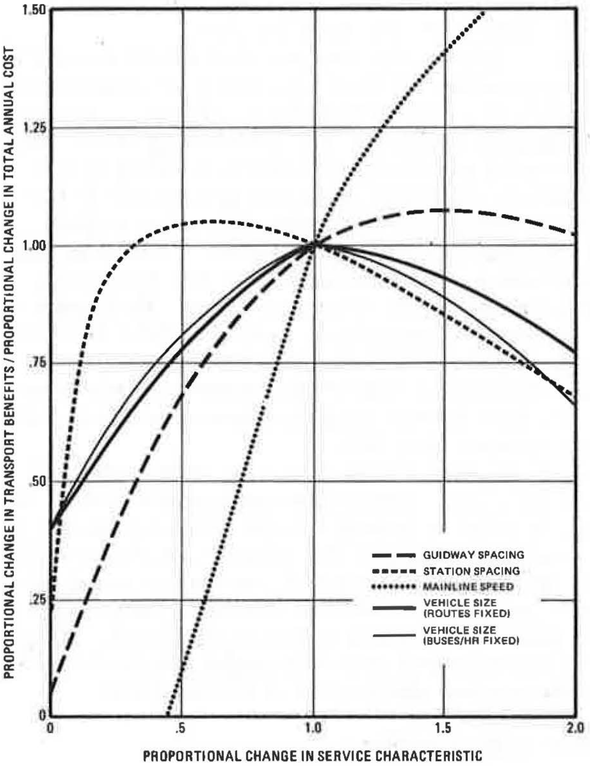

Table 2. Summary of relative sensitivities.

System Output Variable	Relative Sensitivity[a] Speed	Vehicle Size	Miles of Guideway	Station Spacing
Annual costs				
Operating	-0.31	-0.59*	0.05	-0.05
Capital	-0.02	-0.09	0.42*	-0.10
Total	-0.18	-0.37*	0.21	-0.07
Performance				
Average travel time	-0.40*	0.16	-0.23	0.11
Ridership	0.16*	-0.06	0.09	-0.04
Revenues				
Ridership/operating cost	0.47	0.53*	0.05	0
Ridership/total cost	0.34*	0.31	-0.12	-0.03
Benefits				
Annual transport benefits	0.94*	-0.35	0.57	-0.29
Benefits/total cost	1.12*	0	0.36	-0.36

[a] These figures are the slopes at the design point of the curves shown in Figures 1 through 9. The most sensitive service variables have been asterisked.

also provide useful information. For example, by scanning the last column in Table 2, it is readily seen that, by a wide margin, the most sensitive output characteristics to station spacing changes are the benefit-cost ratio and transport benefits.

Perhaps most important, the data given in Table 2 also suggest that annual transport benefits and the transport benefit-total cost ratio for the system studied are themselves most sensitive to changes in main line speed. This means that the single most important service characteristic meriting further examination is guideway speed capability. Any incremental gains in average speed appear to be especially fruitful in relation to the other service characteristics. This conclusion, of course, pertains specifically to the demand-supply context for dual-mode transit simulated within the Milwaukee region.

Sensitivity analyses of the number of guideways, measured in terms of miles of route covering the same service area, show that this service characteristic has most influence on annual capital costs but least influence on annual operating costs. Its impact on total annual costs is thereby moderate. Because it can achieve relatively high benefits at only moderate incremental cost, the number of guideways (or guideway spacing) is also a significant factor to be considered in improving dual-mode transit service characteristics. Relative to the case study, the benefit-cost analysis shows that the number of guideways in the study area should be increased (Fig. 10).

Vehicle size is of greatest importance in affecting annual operating costs and total annual costs. It has a moderate influence on average travel time and expected level of ridership. Because it is relatively costly in relation to only modest incremental changes in transport benefits, vehicle size is of least importance in its influence on the overall benefit-cost ratio. It should be carefully determined in terms of expected demand characteristics. Sensitivity analysis of benefit-cost ratios indicates that an optimum vehicle size for the case study area is the 19-passenger vehicle that was simulated. If for other reasons this vehicle size were to be increased, it would be preferable to do so by also increasing headways, while holding the number and pattern of routes fixed.

PRELIMINARY CONCLUSIONS

It should be stressed that the primary purpose of this paper is not to form firm conclusions regarding dual-mode transit but rather to suggest how a method of parametric analysis might be carried forward. Emphasis should be placed on the method itself, not on the clearly preliminary case study results. Given this qualification, it is felt that the sensitivity analysis techniques discussed here, particularly in the graphical form shown in Figures 2 through 10, do warrant further development and exploration.

Perhaps the most important potential use of these techniques is in better defining optimum service conditions. To further illustrate this potential, the preliminary and illustrative results of the Milwaukee case study are further analyzed. These results also suggest some very tentative conclusions regarding dual-mode transit—the kinds of conclusions toward which new systems implementation efforts should be oriented.

The implications of the data shown in Figure 10 are especially significant here. They illustrate rather clearly the nonoptimization, relative to a maximum benefit-cost ratio, of the system parameters chosen for the dual-mode simulation. These curves suggested that the 19-passenger vehicle used in the case study is approximately the appropriate size. This is the only one of the four service characteristics, however, that achieves a maximum relative to the benefit-cost ratio.

Figure 10 shows that main line speed should be increased as much as possible to optimize the benefit-cost ratio; at the same time local optima for the two remaining characteristics, station spacing and guideway spacing, are also indicated. It must be remembered that these are independently derived optima; therefore, if two or more were to be pursued together, the location of these optimum points would change. It is stressed again that these independent optima are based on selected transport-related benefits only. Conceivably, other community impacts or indirect benefits may be of sufficient value to the community such that they may become more meaningful in determining appropriate system characteristics.

If emphasis is placed on the maximization of the benefit-cost ratio, determined on the basis of direct and indirect transport benefits, the data given in Figure 10 suggest the following changes in service characteristics:

1. Guideway miles—110 to 165 miles,
2. Station spacing—2.75 to 1.65 miles,
3. Main line speed—55 to 70 mph (or greater), and
4. Vehicle size—unchanged.

By factoring each of these suggested service characteristic changes independently into the equations that were used to support the sensitivity analysis, estimates of each of the resulting system output variables can be determined. These data, representing four alternative cases, where one of the characteristics is modified in each case (and subsequently restored in the next case), are given in Table 1. For comparison purposes, a 100 percent increase in vehicle size has also been entered. These data offer another example of how sensitivity analyses can be used to illuminate the importance of different transit service characteristics.

It should be noted that, depending on the service improvement selected, operating costs can be reduced by as much as 33 percent, total costs reduced by 21 percent, fares decreased by 28 percent, benefits increased by 21 percent, and benefit-cost ratio increased by approximately 30 percent. Interestingly, benefit-cost analysis for two service characteristics, guideway spacing and station spacing, suggests an increased investment in guideway facilities—but at a correspondingly increased fare requirement. This represents an aspect of economic feasibility that may argue against the potentially higher benefits to be achieved. In fact, the data shown in Figure 8 suggest that a more desirable revenue-cost ratio for guideway spacing may lie with a decrease in guideway miles to about 80 to 90 percent of simulated values—roughly, seven guideway corridors instead of eight, covering the same transit service region.

It was not suggested in the Milwaukee study that any of these alternative cases represents an acceptable system solution but rather that there are many trade-offs possible, such that a single best solution could not be fully explored within the scope of the case study. On the contrary, the Milwaukee County rapid transit plan system, with which the dual-mode system was repeatedly compared, represents the best of many conventional bus technology trade-offs already examined in that study. It represented the results of a much more intensive, 3-year planning effort. Comparable continuing effort would be required here to identify more preferred and yet locally realistic service configurations.

As a result, the great diversity in potential service configurations for dual-mode transit was emphasized. The sensitivity analyses previously described demonstrated that diversity quite clearly. Although a number of revised service characteristics (guideway spacing, station spacing, etc.) were examined, they are applicable to the Milwaukee area only. Even in this single case study, it was emphasized that further trade-off analyses will be necessary to identify preferred combinations of service features. In other urban areas, particularly those having different residential density patterns, additional studies and trade-off analyses of these same service characteristics will be required (11).

In other cities, both higher and lower service levels may well be indicated. For example, smaller cities, having lower residential densities and a smaller service area, might find a larger vehicle to be preferable. It was stressed that the quality of service simulated in the Milwaukee case study is not necessarily an inherent attribute of dual-mode transit. All of the four service characteristics could be varied to suit local conditions (as could other system features such as the proportion of captive vehicles). The operational flexibility of the dual-mode concept, as demonstrated by these sensitivity analyses, is consequently one of its greatest assets. The dual-mode transit approach closes few urban transportation options and opens up a host of new operating strategies that are not now options in conventional bus systems.

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APPENDIX

CASE STUDY EQUATIONS AND ASSUMPTIONS

The following tables are based on hypothetical data derived from a full-scale dual-mode simulation system (4, 9, 10). Cost and travel time data are based on simulation model outputs and preliminary unit operating and capital cost analyses.

Table 3. Main line speed analyses.

Independent Variable, x_1 = Proportion of Base Line Value, Main Line Speed (mph)

Dependent Variable	Estimating Equation	Comments
y_1 = Proportion of base line value, annual operating cost	$y_1 = \underbrace{.630}_{\text{Proportion of operating costs unaffected by main line speed (63.0\%)}} + \underbrace{.353/x_1}_{\text{Vehicle-based operating costs (35.3\%)}} + \underbrace{.017(2.67x_1 -1.671)}_{\text{Power consumption costs (1.7\%). Sub-equation derived from technical studies}}$	x_1 increase
	$y_1 = .630 + .353/x_1 + .017(1.69x_1 -.692)$	x_1 decrease
y_2 = Proportion of base line value, annual capital cost	$y_2 = \underbrace{.848}_{\text{Proportion of capital costs unaffected by main line speed (84.8\%)}} + \underbrace{.0949/(.735 + .265x_1)}_{\text{Vehicle capital costs affected by speed capabilities (9.49\%). Sub-equation derived from technical studies}} + \underbrace{.0096/x_1}_{\text{Supporting facilities capital costs (.96\%)}} + \underbrace{.047(.735 + .265x_1)}_{\text{Power substation capital costs (4.7\%)/. Sub-equation derived from technical studies}}$	x_1 increase
	$y_2 = .848 + .0949/(.652 + .348x_1) + .0096/x_1 + .047(.652 + .348x_1)$	x_1 decrease
y_3 = Proportion of base line value, average travel time	$y_3 = \underbrace{.598}_{\text{Non-guideway travel time (Neighborhood collection, walk, wait, ramps, enroute stops) (59.8\%)}} + \underbrace{.402/x_1}_{\text{Guideway travel time, at main line speeds (40.2\%)}}$	

Table 4. Main line speed assumptions.

Operating Costs--As main line speed is increased, it becomes possible to reduce the total number of vehicles required. 87.8% of total annual operating costs depend on the number of vehicles in the fleet (all vehicle-based operating costs, excluding guideway operation and maintenance). 40.2% of the travel time for the average transit vehicle is spent at main line speed. Consequently, 35.3% (40.2 x 87.8) of annual vehicle-based operating costs may be assumed to be variable with changes in main line speed. This is an inverse relationship. In addition, minor changes in power consumption costs will also occur.

Capital Costs-- Most annual capital costs--84.8%--will be unaffected by changes in main line speed. The same investments in right-of-way, guideway construction, guidance hardware, and stations will still be required. Adjustments in capital costs for vehicles and supporting garage facilities to reflect changes in fleet size (due to changes in main line speed) must be made. 40.2% of the average vehicle trip spent at main line speeds is used as a multiplier. 23.5% of total annual capital costs are required for vehicle purchase, but only 40.2% of these costs will be inversely variable with main line speed (40.2 x 23.5 = 9.49%). Separate technical studies also showed that per unit vehicle costs would increase slightly with greater speed capabilities (and vice versa), so that separate sub-equations were also estimated for inclusion in the inverse vehicle cost/speed relationships. Similar calculations for supporting facilities capital costs were also made (40.2 x 2.4 = .96%). Separate technical equations were also estimated to reflect changes in power substation capital costs (4.7% of total) due to greater guideway speed capabilities.

Average Travel Time-- 59.8% of the average person trip will be spent off the guideway. The remaining 40.2% of overall average travel time will vary inversely with changes in main line guideway speed.

Table 5. Vehicle size analyses.

Independent Variable, x_2 = Proportion of Base Line Value, Number of Seats per Vehicle

Dependent Variable	Estimating Equation	Comments
y_1 = Proportion of base line value, annual operating cost	$y_1 = \underbrace{.105}_{\text{Proportion of operating costs unaffected by vehicle size (10.5\%)}} + \underbrace{.475/x_2}_{\text{Operator wages, superintendence and misc. vehicle-based costs (47.5\%)}} + \underbrace{.403/(.71+.29x_2)}_{\text{Vehicle maintenance, fuel, and oil costs (40.3\%). Sub-equation based on technical studies}} + \underbrace{.017(.825+.175x_2)}_{\text{Power consumption costs (1.7\%). Sub-equation based on technical studies}}$	x_2 increase
	$y_1 = .105 + .475/x_2 + .403/(.54+.46x_2)+.017(.50+.50x_2)$	x_2 decrease
y_2 = Proportion of base line value, annual capital cost	$y_2 = \underbrace{.740}_{\text{Proportion of capital costs unaffected by vehicle size (74.0\%)}} + \underbrace{.236/(.71+.29x_2)}_{\text{Vehicle capital costs (23.6\%). Sub-equation based on technical studies}} + \underbrace{.024/x_2}_{\text{Supporting facilities capital costs (2.4\%)}}$	x_2 increase
	$y_2 = .740 + .236/(.54+.46x_2) + .024/x_2$	x_2 decrease
y_3 = Proportion of base line value, average travel time	$y_3 = \underbrace{.878}_{\text{Proportion of average travel time unaffected by vehicle size}} + \underbrace{.051x_2}_{\text{Travel time spent at en route stops (5.1\%)}} + \underbrace{.071x_2}_{\text{Average wait time (7.1\%)}}$	Number of routes held fixed
	$y_3 = .842 + .051x_2 + \underbrace{.107x_2}_{\text{Average walk time (10.7\%)}}$	Number of buses/hour held fixed

Table 6. Vehicle size assumptions.

Operating Costs--	10.5% of total annual operating costs, those due to guideway operation and maintenance, will remain fixed. 47.5% of operating costs will vary inversely with the total number of buses (fleet size). These will include driver wages, driver superintendence, operating garage wages, insurance, and other miscellaneous operating costs. 40.3% of operating costs will vary inversely with vehicle size, including depreciation, maintenance, parts, tires and tubes, fuel and oil. The relationship of these costs to vehicle size is assumed to be the same as that for vehicle capital costs.
Capital Costs--	26% of annual capital costs will vary inversely with vehicle size, reflecting vehicle purchase, and construction of supporting facilities (operating garages, maintenance garages). Separate studies of the relationship of vehicle capital costs and vehicle size were conducted. The remaining 74% of capital costs will remain fixed, covering right-of-way purchase, guideway construction, guidance hardware, stations, and power distribution.
Average Travel Time--	When vehicle size is altered, either the number of buses per hour (headways) or the number of routes within a given neighborhood must be correspondingly adjusted to meet the assumed fixed demand. If the number of routes per neighborhood is altered, the walk time will be changed. If headways are varied instead, then the corresponding wait time will be altered. Vehicle size will also affect the dwell time spent at enroute stops along the line-haul portion of the average trip. All three of these time components were assumed to vary directly with vehicle size.

Table 7. Guideway spacing analyses.

Independent Variable, x_3 = Proportion of Base Line Value, Total Guideway Mileage

Dependent Variable	Estimating Equation
y_1 = Proportion of base line value, annual operating cost	$y_1 = \underbrace{.954}_{\text{Proportion of operating costs unaffected by guideway spacing (95.4\%)}} + \underbrace{.046x_3}_{\text{Guideway-based operating costs (excluding CBD) (4.6\%)}}$
y_2 = Proportion of base line value, annual capital cost	$y_2 = \underbrace{.578}_{\text{Proportion of capital costs unaffected by guideway spacing (57.8\%)}} + \underbrace{.422x_3}_{\text{Guideway-based capital costs (excluding CBD) (42.2\%)}}$
y_3 = Proportion of base line value, average travel time	$y_3 = \underbrace{.771}_{\text{Walk, wait, and guideway travel time (77.1\%).}} + \underbrace{.229/x_3}_{\text{Neighborhood collection/distribution travel time (22.9\%)}}$

Table 8. Guideway spacing assumptions.

Operating Costs--	Operating costs dependent upon total miles of guideway amount to only 4.6% of total annual operating costs. They do not include any costs relating to the total number of vehicles or vehicle miles, which are assumed to remain constant, and therefore include only guideway operation and maintenance cost items. Operation and maintenance cost for CBD guidway links and stations have, however, been excluded, since these facilities are assumed to remain fixed as well. Similarly, costs for power consumption and control complex maintenance have also been assumed to remain fixed.
Capital Costs--	Any increase in guidway mileage, for a fixed service area, was assumed to imply the construction of an additional segment in an additional service corridor, or a closer network spacing. A much higher percentage of total annual capital costs is related to the total miles of guideway in the system. 42.2% of total annual costs will vary directly with the number of miles of guideway. In fact, these will include all capital cost expenditure items except those for vehicles, supporting facilities, CBD tunnel, and CBD stations.
Average Travel Time--	Change in the number of guideways is assumed to have impact only upon the amount of travel time spent in neighborhood collection and/or distribution. That is, if the pattern of neighborhood routings is assumed to remain the same, as well as headways, there will be no effect upon walk or wait times, nor will there be any change in ramp or line-haul travel times. The assumed relationship is a reciprocal one. That is, if the number of guideways are doubled, the average collection time will be halved, since it will now be much easier to reach the nearest guideway from any neighborhood collection point. Nine minutes or 22.9% of the average dual-mode trip was spent in neighborhood collection.

Table 9. Station spacing analyses.

Independent Variable, x_4 = Proportion of Base Line Value, Average Mileage Between Stations

Dependent Variable	Estimating Equation
y_1 = Proportion of base line value, annual operating cost	$y_1 = \underbrace{.954}_{\text{Proportion of operating costs unaffected by station spacing (95.4\%)}} + \underbrace{.046/x_4}_{\text{Station-based operating costs (excluding CBD) (4.6\%)}}$
y_2 = Proportion of base line value, annual capital cost	$y_2 = \underbrace{.898}_{\text{Proportion of capital costs unaffected by station spacing (89.8\%)}} + \underbrace{.102/x_4}_{\text{Station-based capital costs (excluding CBD) (10.2\%)}}$
y_3 = Proportion of base line value, average travel time	$y_3 = \underbrace{.369}_{\text{Walk, wait, and ramp portions of average travel time (36.9\%)}} + \underbrace{.229x_4}_{\text{Neighborhood collection/distribution travel time (22.9\%)}} + \underbrace{.402(1.30-.30x_4)}_{\text{Main line guideway travel time (40.2\%). Sub-equation separately derived}}$

Table 10. Station spacing assumptions.

Operating Costs--	Annual operating costs dependent upon the number of stations in the system (excluding CBD stations, which are assumed to remain fixed) included the costs for station personnel, control complex maintenance, and 75.9% of control hardware maintenance costs (the latter reflecting the fact that most of the system control hardware will be located within station areas, where most of the merge, acceleration and deceleration activities will take place). Only 4.6% of total annual operating costs are represented in this variable relationship.
Capital Costs--	The annual capital costs for the 40 stations within the hypothetical guideway network (again excluding CBD stations) represented some 10.2% of total annual capital costs. These covered the costs for right-of-way, station facility, automation hardware, power hardware, and ramps within each station area. Changes in both operating and capital costs hold a reciprocal relationship with any change in the number of miles between stations. That is, as this mileage is doubled, related systems costs would halve, and vice versa.
Average Travel Time--	It was assumed that any change in station spacing would have no effect upon walk, wait or ramp times for the average dual-mode trip. However, in addition to a likely change in the neighborhood collection/distribution travel time, station spacing will also affect the amount of time spent in the line-haul portion of the average trip. That is, a trade-off between neighborhood and line-haul time will occur, for a given guideway configuration. As more stations appear in the system, less time for neighborhood collection will be required, due to more direct routings, correspondingly increasing the trip time spent on the guideway itself. A direct relationship with changes in both neighborhood collection/distribution time and main line guideway travel was assumed.