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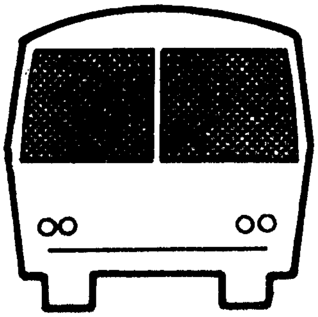
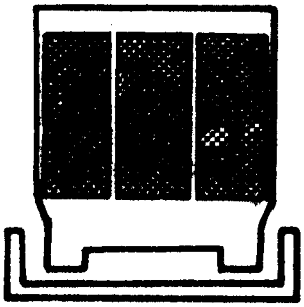
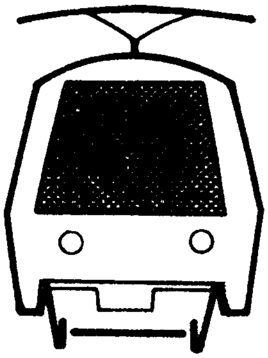
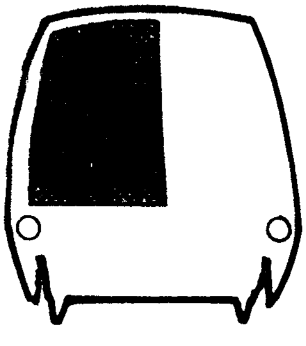
TECHNICAL MEMORANDUM NO. 4

TRADE-OFF ANALYSIS METHODOLOGY









North Central Texas Council of Governments

TEXAS TRANSPORTATION INSTITUTE
TEXAS A&M UNIVERSITY SYSTEM

Technical Memorandum No. 4

TRADE-OFF ANALYSIS
METHODOLOGY

Submitted to

North Central Texas Council of Governments

Arlington, Texas

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by

Texas Transportation Institute
Texas A&M University System
College Station, Texas

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INTRODUCTION

Current long-range transportation plans for the Dallas-Fort Worth Metropolitan Area call for the development of several transitways by 1990. These transitways will initially operate with buses and carpools; however, future conditions may make the transition from buses to some other form of mass transit along these same rights-of-way desirable. Hence, the feasibility of designing transit facilities that can be easily adapted to various forms of mass transportation is a legitimate concern.

"Transit Technology Selection Analysis for the Dallas-Fort Worth Intensive Study Area" is a study designed to evaluate the feasibility and desirability of designing transitways that can evolve from one form of mass transportation to others. The objectives of this study are as follows:

1. Identify logical evolutionary paths associated with various stimuli for change (capacity, labor intensity, energy considerations, etc.) from buses and evaluate the conditions under which a change in technology would be desirable.
2. Develop a set of alternative transitway designs and evaluate the feasibility and/or limitations of transition from buses to other technologies using each alternative design.
3. Identify pertinent trade-off considerations and implications associated with the evolutionary transitway concept and evaluate the desirability of this approach.

As a first step in the study, an extensive literature survey was conducted and an annotated bibliography ("Transitway Technology: An Annotated Bibliography") was prepared as the first technical memorandum of the study.

The results of studies conducted to satisfy Objective 1 were documented in a second technical memorandum ("Analysis and Selection of Transitway Evolutionary Paths"). The following evolutionary paths were identified for design evaluation:

(1) Reference Design #1: Narrow Guideway for Buses Only (BRT)*,

(2) Reference Design #2: Wide Guideway for Buses and Carpools,

(3) Evolutionary Path #1: Bus/Carpool →
    BRT → Automated Guideway
    Transit (AGT) with Off-line Stations,

(4) Evolutionary Path #2: Bus/Carpool →
    BRT → Rail Rapid Transit (RRT) with On-line Stations, and

(5) Evolutionary Path #3: BRT →
    Rail Rapid Transit (RRT) with On-line Stations.

Conceptual design approaches for each of the five items listed above were developed and documented in a third technical memorandum ("Alternative Evolutionary Design Approaches"). In essence, the third technical memorandum documents the results of the work performed to satisfy the first portion of Objective 2.

The purpose of this fourth technical memorandum is to document the methodology used in performing trade-off studies concerning the evolutionary concept. A final report that presents a summary of the total study findings with appropriate conclusions and recommendations will be prepared subsequently.

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*Bus Rapid Transit

COST ESTIMATES

In order to evaluate the economic advisability of constructing an evolutionary guideway design, it is necessary to estimate the cost impacts for such designs. Of course, estimating costs for conceptual designs is, at best, an approximate process because actual costs will vary so much between different specific designs that fall within a design concept. For example, the costs for a deluxe version of a system (such as BART) can be double or triple those for a "plain vanilla" version (such as Lindenwold Line). Hence, the objective of this cost estimation effort was to accurately define the relative costs of the various designs. The resulting cost estimates should not be interpreted as valid estimates of the absolute costs for any individual design.

General Cost Data

For the purpose of this analysis, it was assumed that the initial system for each design would consist of the following components:

- 30 miles of elevated guideway,
- 30 miles of at-grade guideway,
- 30 park-and-ride lots near future station locations,
- 2 maintenance yards and shops for buses.

The major cost items associated with the transition were assumed to be the following:

- 5 miles of subway system in CBD's
- 7 subway stations in CBD's
- Conversion of 60 miles of existing guideway (i.e., track, power, control, etc.),

- 30 stations along existing guideways,
- Guideway vehicles (1200 AGT or 700 RRT), and
- 2 maintenance yards and shops for guideway vehicles.

The reference cost values used in developing these cost estimates are listed in Table 1. Most of these reference values came from one of the following sources:

1. Bus Rapid Transit Options for Densely Developed Areas (1)*,
2. Characteristics of Urban Transportation Systems (2),
3. Rail Transit System Cost Study (3), or
4. Pittsburg-Antioch BART Extension Project Final Report (4).

All of the reference cost values are based on 1973 costs. These were not adjusted to a later year because the objective of this analysis was to develop relative costs rather than planning values. It was assumed that inflation would impact various designs to a similar degree so that the relative costs would remain the same.

For the purposes of this study, it was assumed that new rights-of-way would have to be obtained for any transitway system that might be built. Right-of-way costs were estimated accordingly, using the values shown in Table 1. This element of the cost estimates is probably the least accurate of all. Hopefully, much of the right-of-way will be adjacent to an existing railroad, street, or freeway and will not be as expensive as estimated. Indeed, there is some hope that portions of the transitway--particularly if the narrow design is used--could be placed within existing rights-of-way for other facilities. Thus, the final costs for right-of-way may be significantly different than the estimates used in this study.

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*Denotes number of reference listed at end of report.

Table 1: Reference Cost Values

	Guideway Design	
	Narrow	Wide
Reference Designs		
Right-of-Way Costs	$1.0M/mile	$1.9M/mile
Elevated Guideway Structure	4.3M/mile	6.5M/mile
At-Grade Guideway	1.0M/mile	1.5M/mile
Ramps	$1M/station	
Park & Ride Lots & Land for Station	1M/station	
Buses	45,000 each	
Conversion Costs on Initial System		
Trackwork for RRT	$0.8M/mile	
Sidewalls for AGT	0.5M/mile	
Power System (AGT or RRT)	0.9M/mile	
Control System for RRT	0.8M/mile	
Control System for AGT	1.0M/mile	
Stations	2.6M each	
Vehicles - RRT	0.35M each	
Vehicles - AGT	0.20M each	
Other Transition Costs		
Subway in CBD's	$40M/mile	
Subway Stations in CBD's	12M each	
Vehicle Maintenance Facilities	10M each	

Note: These cost values are based on 1973 costs.

Sources of Data: References (1), (2), (3), and (4).

The major differences in the Reference Designs and the designs for various Evolutionary Paths that have an impact on the initial costs are the raceways for future power and control cables and the additional structural strength required for eventual RRT operation. The costs for providing raceways was estimated to be an additional $0.2M per mile for each of the Evolutionary Designs. The procedures used for estimating the cost impact of the additional structural strength are described in the following two paragraphs.

Analysis performed by Dr. John Haynes, et al, in a previous study (5), established the relative bending moment induced by an RRT vehicle at 2.1 times that imposed by a bus. Using these relative loads, several different elevated structure designs were identified and their costs estimated. The resulting cost ratios varied from 1.75 to 2.0 with the average being 1.85. Thus, the cost impact of the increased structural strength needed for RRT systems was estimated to be 85 percent of the cost of the narrow elevated guideway for buses--or an additional $2.67M per mile of elevated guideway.

The cost impact of the increased load capability of an at-grade portion of the guideway was estimated to be 50 percent of the cost of the narrow roadway for buses--or an additional $0.5M per mile of at-grade guideway. This 50 percent increase is consistent with planning estimates used for highways and airport runways designed to accommodate vehicles weighing twice as much.

These general cost data were used to develop cost estimates for each design. Specific cost estimates for each design are presented in the following paragraphs.

Reference Design #1

Reference Design #1 is the narrow 2-lane busway; however, a total of ½ mile of guideway will be wider to accommodate acceleration/deceleration lanes at each station. Because station spacing is approximately 2 miles, approximately 25% of the guideway will be wide. This ratio of 75% narrow/25% wide is reflected in the cost estimate.

		Millions of Dollars
R.O.W.:	45 miles @ $1.0 M/mi	45.0
	15 miles @ $1.9 M/mi	28.5
Elevated Guideways:	22.5 miles @ $4.3 M/mi	96.8
	7.5 miles @ $6.5 M/mi	48.7
At-grade Guideways:	22.5 miles @ $1.0 M/mi	22.5
	7.5 miles @ $1.5 M/mi	11.25
Ramps:	30 stations @ $1.0 M each	30.0
Park-and-Ride Lots:	30 @ $1.0 M each	30.0
Vehicles:	1200 @ $45,000 each	54.0
Maintenance Facilities:	2 @ $10 M each	20.0
	TOTAL	386.8

Round off to $390 million.

Reference Design #2

This design is the wide busway. The continuous shoulders will be used as acceleration/deceleration lanes as that the width will be uniform throughout.

		Millions of Dollars
R.O.W.:	60 miles @ $1.9 M/mi	114
Elevated Guideway:	30 miles @ $6.5 M/mi	195
At-grade Guideway:	30 miles @ $1.5 M/mi	45
Ramps:	30 @ $1.0 M each	30
Park-and-Ride Lots:	30 @ $1.0 M each	30
Vehicles:	1200 @ $45,000 each	54
Maintenance Facilities:	2 @ $10 M each	20
	TOTAL	488

Round off to $490 million.

Evolutionary Design #1

This is the wide guideway designed to accommodate Bus/carpools → BRT → AGT. The initial cost of this guideway will be the same as for Reference Design #2 except for the cost of installing raceways for future power and control cables.

Based on data from BART (4) and Dyer (3), the total cost for the power and control system for an RRT system is:

Power distribution:	$0.75 to $1.0 million/mile
Control system:	$0.65 to $2.65 million/mile
TOTAL:	$1.4 to $3.6 million/mile

No data are available on the marginal costs of providing raceways in structures; however, it seems reasonable to assume that the raceways would constitute no more than 10% of the system cost. Thus, a value of $0.2 million/mile is assumed for raceways.

The resulting initial cost of Evolutionary Design #1 is then:

• Cost of Reference Design #2	$490 Million
• Cost of Raceways 60 miles @ $0.2 M/mi	12 Million
TOTAL	$502 Million

Round off to $500 million.

The transition costs for converting this guideway from BRT to AGT operation were estimated as follows:

		Millions of Dollars
• Convert existing guideways (60 miles)		
Sidewalls	60 mi @ $0.5 M/mi	30
Power	60 mi @ $0.9 M/mi	54
Control System	60 mi @ $1.0 M/mi	60

	Millions of Dollars
• CBD Portion (all new)	
Subway: 5 miles x $40 M/mi	200
Subway Stations: 7 @ $12 M each	84
• Stations on Existing Routes	
30 @ $2.6 M each	78
• Vehicles	
1200 @ $0.2 M each	240
• Maintenance Yards	
2 @ $10 M each	20
TOTAL	766

Round off conversion costs to $770 million.

Envolutionary Design #2

This is a wide guideway that is designed with sufficient structural capability to support RRT. The difference in costs between this design and Reference Design #2 are as follows:

1.) Cost of raceways for power and control system, and

2.) Cost of additional structural strength.

The resulting estimated cost of the initial design was calculated as follows:

	Millions of Dollars
• Cost of Reference Design #2	490
• Cost of Raceways	12
• Cost of added structural strength	
elevated portions: ($4.3 M/mi x 0.85) x 30	110
at-grade portions: ($1.0 M/mi x 0.5) x 30	15
TOTAL	627

Round off to $630 million.

The costs for converting Evolutionary Design #2 from BRT to RRT operation were estimated as follows:

	Millions of Dollars
● Convert existing guideways	
Trackwork 60 mi @ $0.8 M/mi	48
Power 60 mi @ $0.9 M/mi	54
Controls 60 mi 2 $0.8 M/mi	48
● CBD portions	
5 miles x $40 M/mi	200
7 stations x $12 M each	84
● Stations on existing routes	
30 stations @ $2.6 M each	78
● Vehicles (700 @ $0.35 M each)*	245
● Maintenance yards (2 @ $10 M each)	20
	777

Round off to $780 million.

Evolutionary Design #3

This design is a narrow guideway with sufficient structural capability to accommodate RRT operation. The cost for the initial system was estimated as follows:

● Cost of Reference Design #1	$390 Million
● Cost of Raceways	$ 12 Million

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*Note: 700 RRT vehicles provide equivalent seating capacity to 1200 buses or 1200 AGT vehicles.

• Cost of Added Structural Strength	$125 Million
	$527 Million

Round off to $530 million.

The transition costs for this design are estimated to be the same as for Evolutionary Design #2--or $780 Million.

Summary of Specific Cost Estimates

The resulting cost estimated for all five system designs are summarized in Table 2. It should be noted once again that these estimates are based on 1973 cost data; they are not valid estimates of actual costs that would be incurred at some future date. However, the relative costs of the various designs should remain reasonably constant.

Table 2: Estimated Cost of System Designs

Design	Initial Cost	Transition Cost
Reference Design #1 (Narrow Busway)	390	N/A
Reference Design #2 (Wide Busway)	490	N/A
Evolutionary Path #1 (Wide: BRT → AGT)	500	770
Evolutionary Path #2 (Wide: BRT → RRT)	630	780
Evolutionary Path #3 (Narrow: BRT → RRT)	530	780

Note: Costs are in millions of 1973 dollars.

The additional initial investment required to construct a design suitable for evolving to AGT operations (Evolutionary Path #1) is negligible compared to the cost of a wide busway. As mentioned previously, the design for Evolutionary Path #2 could be considered a "universal guideway" design; however, this design costs about 30 percent more than the wide busway for the initial portion. The initial investment in Evolutionary Path #3 is 36 percent more than for the comparable narrow busway. Obviously, the major difference in the initial costs for evolutionary designs compared to a similar busway design is the added structural capability needed to support rail rapid transit vehicles.

The estimated transition costs for various evolutionary designs are virtually the same. The total estimated transition cost in each case is composed of three major components of almost equal costs as shown below:

1. Convert existing guideways ≈$230M,
2. Construct CBD portions ≈ $280M, and
3. Vehicles and maintenance yards ≈ $270M.

Of course, these are costs that would not be incurred unless a transition from buses to another technology actually occurs.

Presumably, if such a transition ever does occur, the initial added investment in the evolutionary design would prove to be a wise investment. However, the results of present value analyses, discussed in the following section, indicate that this presumption may not necessarily be valid.

PRESENT VALUE ANALYSES

The results of analyses of system attributes discussed in Section II of this report indicated a strong probability that a transition from buses to any other mode might never occur. Of course, if such a transition is never needed, then the additional monies expended to build evolutionary designs initially would seem to have been a poor investment. No additional economic analyses are needed to evaluate this eventuality.

If, however, sufficient stimuli should develop at some future date to justify a transition in modes, the initial investment in an evolutionary design may have been a wise investment. In order to evaluate the economic value of evolutionary design, present value analyses were performed for two possible courses of action that would yield the same final result. These two courses of action are as follows:

1. Build the evolutionary design initially and make the transition at a future date;
2. Build a busway initially and then, at some future date, do whatever is necessary to convert the system to the subsequent mode of operation (even to the extent of tearing out and replacing structures).

Each of these courses of action would require a different total investment, but what is more important is that different portions of the total investment would be required at different times. Hence, present value analyses are needed to evaluate the economic trade-offs between these various courses of action.

Present value analysis is a technique that is frequently used to evaluate alternative proposals that involve capital expenditures. The present value concept recognizes the time value of money; since money can be invested at an interest rate, one dollar received today is worth more than one dollar received five years from now.

The discount, or interest, rate involved in the analysis reflects the costs of obtaining the required monies or, in other words, the opportunity cost associated with the investment. This rate is applied to future cash flows to ascertain their present value. In theory, the alternative with the lowest present value, assuming the benefits recieved from all alternatives are equal, is the preferred course of action.

Whereas the discount rate establishes the cost of obtaining funds, the inflation rate establishes the magnitude of future expenditures. In effect, the inflation rate at least partially offsets the discount rate. If both the discount rate and the inflation rate are equal, there will be no reason to use the present value analysis since it will yield the same results as an analysis of total project costs, not considering the timing of expenditures. If the discount rate exceeds the inflation rate, some benefits will accrue from postponing expenditures. Conversely, if the inflation rate exceeds the discount rate, it will be beneficial to make immediate investments rather than postpone expenditures.

Thus, to an extent, the significance of using present value analysis in evaluating the evolutionary transitway concept is dependent upon the relationship between the discount rate and the inflation rate. Trends in both the consumer price index and the federal aid highway construction index are plotted in Figure 1. From 1945 to 1969 these two indices followed each other fairly closely, increasing at an average annual compound rate of 2.25 percent. For two years, since 1969, namely, 1969 to 1970 and 1973 to 1974, the construction index increased at a much more rapid rate than did the consumer price index.

However, since this only occurred during 2 of the 30 years shown, it can hardly be considered to be a trend. From 1969 to 1975 the construction index increased by 82 percent, or an average annual compound rate of 10 percent. Thus, even during this period of the most rapid growth in the construction index, its rate of growth was only equal to the 10 percent discount rate specified by the federal government for all federal investments.

No attempt is made in this study to project either the discount rate or the inflation rate that might be appropriate in the future years. At present, the generally accepted discount rate is 10 percent. It is anticipated that inflation will continue in the future, and this inflation will, in effect, lower the value of the appropriate discount rate. As a consequence, both a 10 percent and a 5 percent discount rate were considered in this analysis.

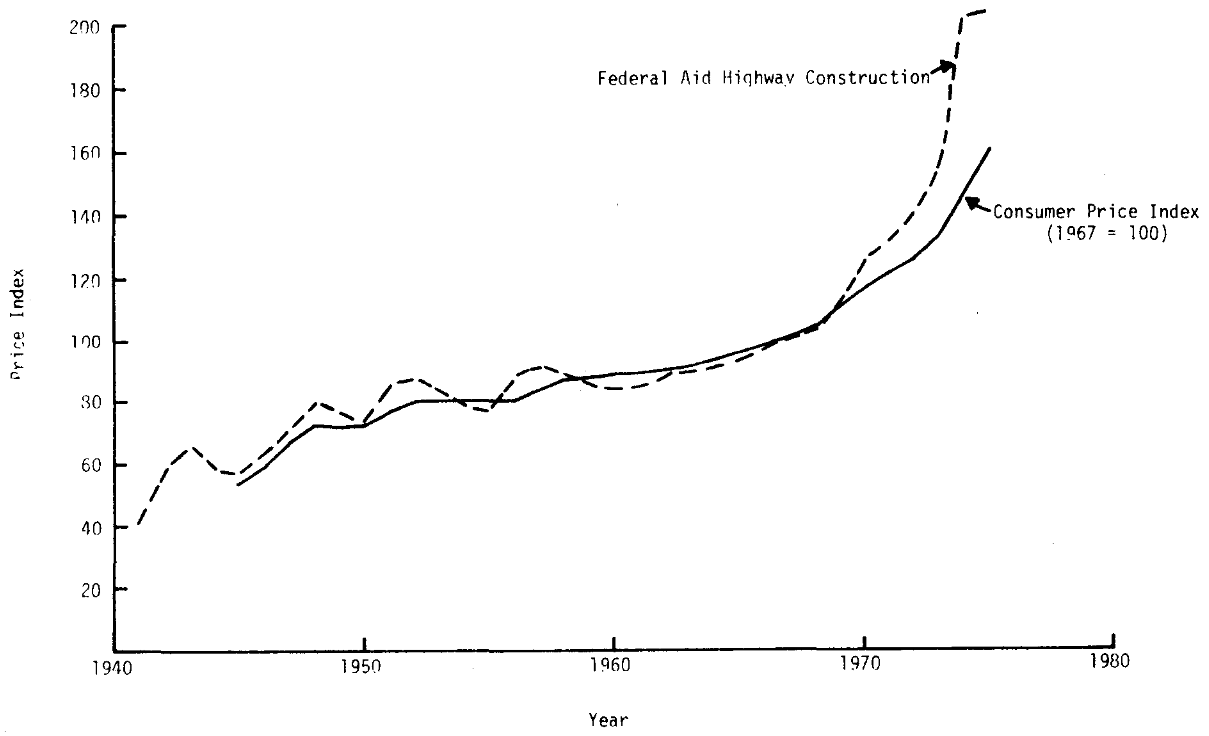

Figure 1: Trends in Price Indices

Evolutionary Path #1 (Wide: Bus/carpool → BRT → AGT)

If the ultimate operational technology is expected to be AGT, then the two courses of action are as identified below.

- Evolutionary Path #1 - Construct a wide evolutionary guideway and operate buses initially, with a transition to AGT at some future date.
- Alternate Approach #1 - Construct a wide busway initially and then modify it as necessary to accommodate AGT at some future date. This would entail the addition of raceways to existing structures at an estimated cost of $30 million and then converting to AGT.

The estimated costs for these two courses of action are presented in Table 3, and the present value is presented in Figure 2. For this particular path, there is very little difference in costs between the two courses of action.

Table IV-3: Cost Estimates for Various Courses of Action Toward AGT Operation

Course of Action	Initial Cost	Transition Cost
Evolutionary Path #1 (Evolutionary Design)	500	770
Alternate Approach #1 (Busway Modified)	490	800

Note: Cost estimates are in millions of 1973 dollars.

Evolutionary Path #2 (Wide: Bus/carpool→ BRT→ RRT)

The two courses of action evaluated for this option are identified below.

- Evolutionary Path #2 - Construct the evolutionary guideway design (wide and strong) initially; operate buses until a transition is made to RRT.

- Alternate Approach #2 - Construct a wide busway (Reference Design #2) initially and then, when it is time for the transition, tear out the lightweight busway structures and replace them with wide RRT guideways.

The costs of accomplishing Alternative Approach #2 were estimated as follows:

	Millions of Dollars
• Cost of tearing out existing structure	
60 miles x $1 M/mi	60
• Construct new guideway for RRT	
Elevated: 30 mi x $10.2 M/mi	306
At-grade: 30 mi x $2.0 M/mi	60
Subway: 5 mi x $40 M/mi	200
Trackwork, power, and controls	150
• Stations	
30 @ $2.6 M each	78
7 @ $12 M each	84
• Vehicles	
700 @ $0.35 M each	245
• Maintenance Yards (2 @ $10 M each)	20
	1,203

Round off to $1,200 million.

The cost estimates associated with these two courses of action are presented in Table 4. The results of the present value analyses are presented in Figure 3.

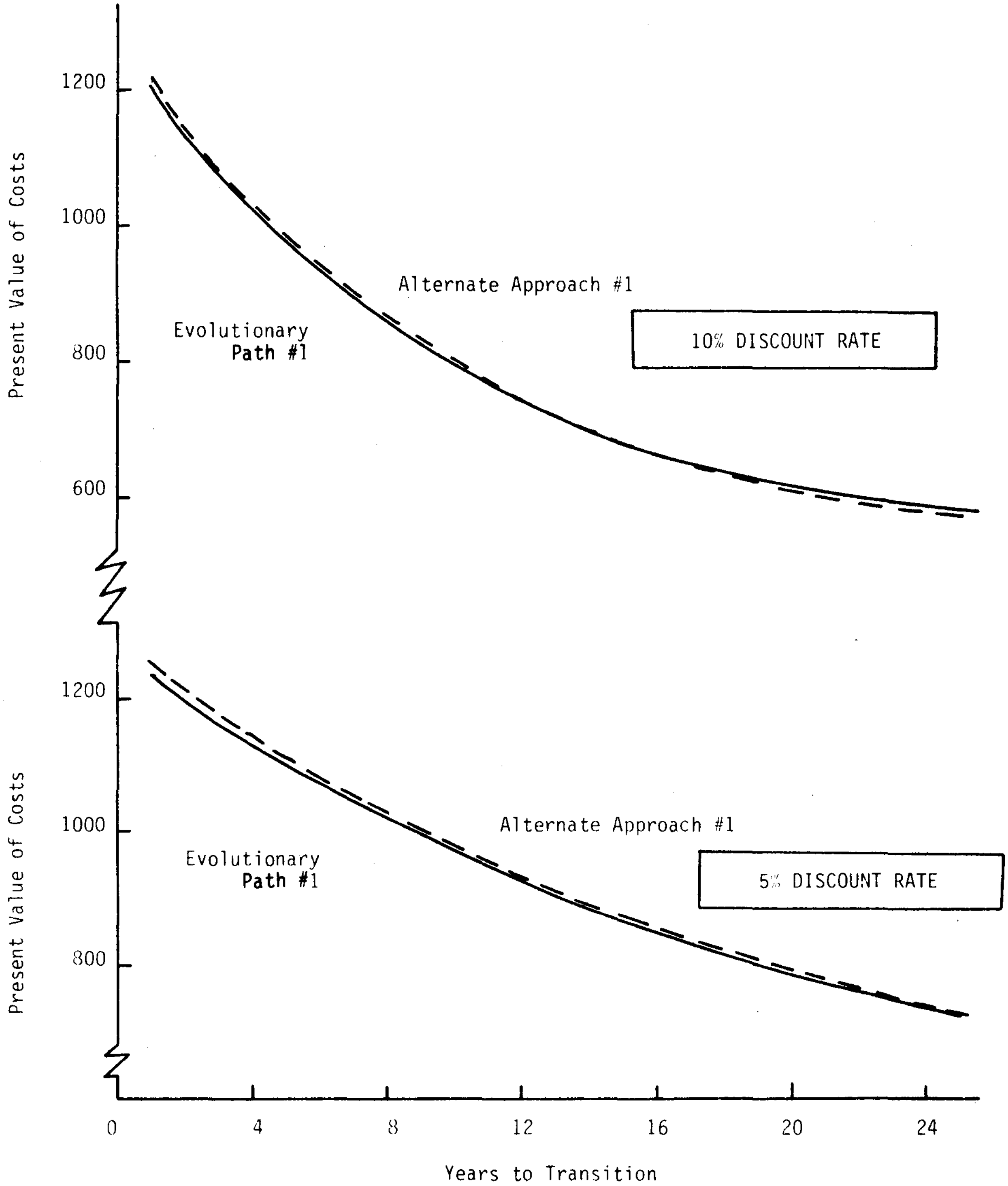

Figure 2: **Present Value of Evolutionary Path #1 and Alternate Approach #1**

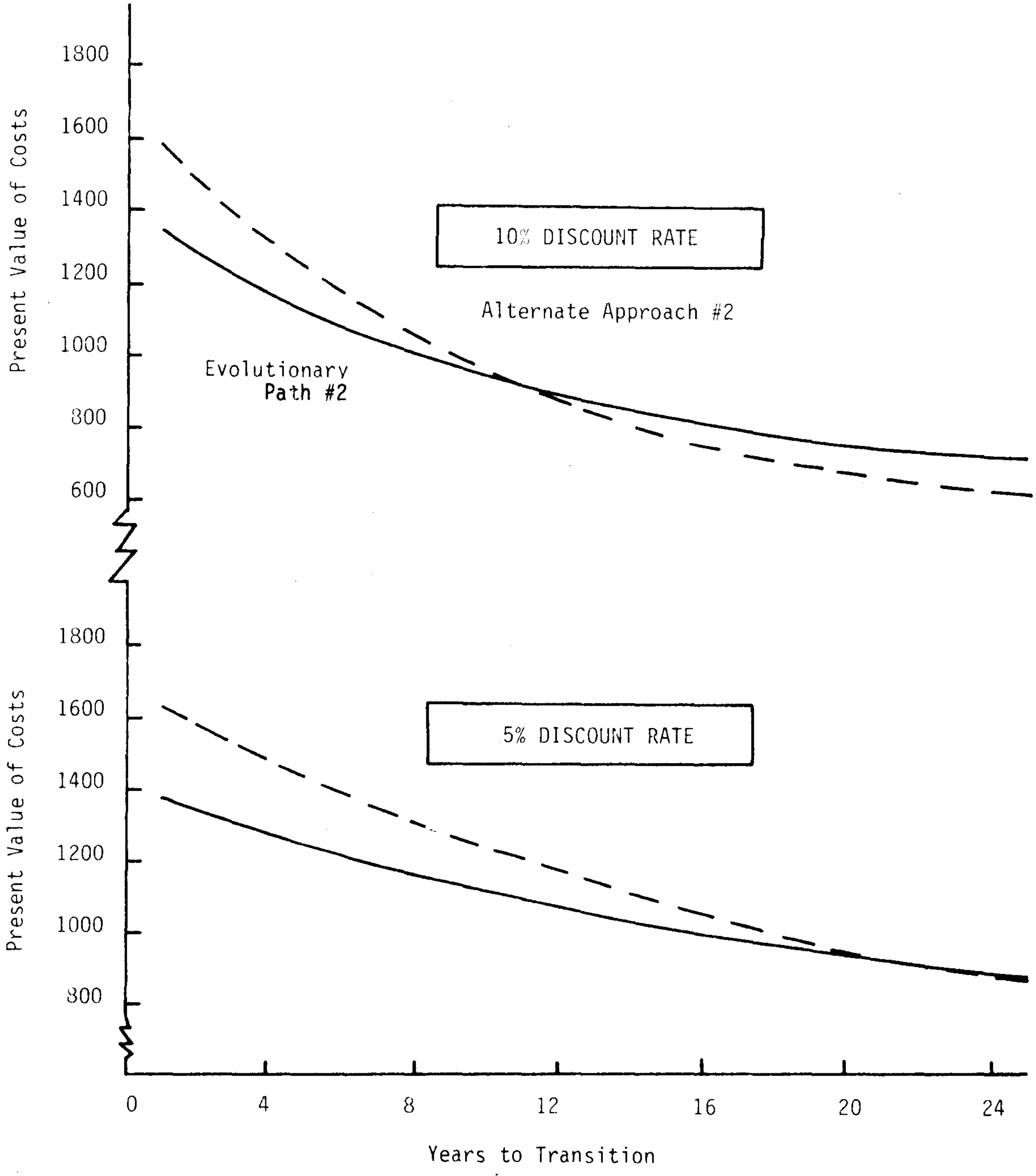

Figure 3: Present Value of Evolutionary Path #2 and Alternate Approach #2

Table 4: Cost Estimated for Various Courses of Action Toward RRT Operation Using a Wide Guideway

Course of Action	Initial Cost	Transition Cost
Evolutionary Path #2 (Wide: BRT → RRT)	630	780
Alternate Approach #2 (Busway → Rebuild Guideway)	490	1200

Note: Cost estimates are in millions of 1973 dollars

An inspection of these present value curves reveals that Evolutionary Path #2 is the lowest cost course of action for a period of years. Finally, if the transition has not already occurred, Alternate Approach #2 replaces Evolutionary Path #2 as the lowest cost option. In other words, the evolutionary approach is the lowest cost option only if the transition to RRT occurs before the 12th year if the effective discount rate is 10 percent or before the 22nd year if the appropriate discount rate is 5 percent. The significant point is that the economic advantages of the evolutionary design diminish as the transition is postponed. Eventually, the alternate approach becomes less costly in terms of present value regardless of the discount rate used in the analysis.

Obviously, this analytical technique is highly sensitive to the discount rate applied (the curves intersect at 12 years with a 10 percent discount rate or at 22 years with a 5 percent discount rate). It is not so obvious that this present value analysis technique is equally sensitive to the cost estimates used in the analysis. For example, if the cost estimates are varied within a range of ± 5 percent, the resulting intersection between the two curves will vary from 12 years to 37 years using a 5 percent discount rate.

As noted previously, cost estimates are seldom accurate to better than ± 10 percent; thus, the results obtained from these present value analyses should not be considered precise--they are only indicative.

Regardless of the sensitivity of this analysis technique to the specific values used, it identifies a very significant condition--the economic benefit of the evolutionary approach diminishes with time. In other words, the longer that the transition is delayed, the less will be the savings accrued from having an evolutionary facility. Indeed, eventually the alternative approach will become the less expensive in terms of present value.

Evolutionary Path #3 (Narrow: BRT → RRT)

The two courses of action evaluated for this option are as follows:

- Evolutionary Path #3 - Construct the evolutionary guideway design (narrow and strong) initially and operate buses until transition to RRT operations at a later date.
- Alternate Approach #3 - Construct a narrow busway initially and then tear it out and replace it with a narrow RRT guideway. The cost estimates for this alternative are the same as for Alternative Approach #2 except for a reduced cost of guideways.

The cost estimates associated with these two courses of action are presented in Table 5. The results of the present value analyses are presented in Figure 4.

It should be noted that the range of years to transition shown on Figure 4 is 50 years rather than the 25-year period plotted on the two previous figures. This longer time span emphasized an inherent characteristic of present value analyses involving two separate investments. That characteristic is that the

Table 5: Cost Estimates for Various Courses of Action Toward RRT Operation Using A Narrow Guideway

Course of Action	Initial Cost	Transition Cost
Evolutionary Path #3 (narrow: BRT → RRT)	530	780
Alternate Approach #3 (Busway → Replace Guideway)	390	1120

Note: Costs are in millions of 1973 dollars.

longer the second investment is postponed, the closer the present value will approach the cost of the original investment. For example, using a 10 percent discount rate, the present value of Alternate Approach #3 is only $400M after 50 years, compared to an original cost of $390M.

A significant implication of this characteristic is that, even though the alternate approach eventually replaces the evolutionary design as the lowest cost option, the present value difference in costs will never exceed the difference in initial costs. Thus, the total monetary risk associated with an evolutionary design is defined by the differences in initial costs of a busway and the evolutionary transitway.

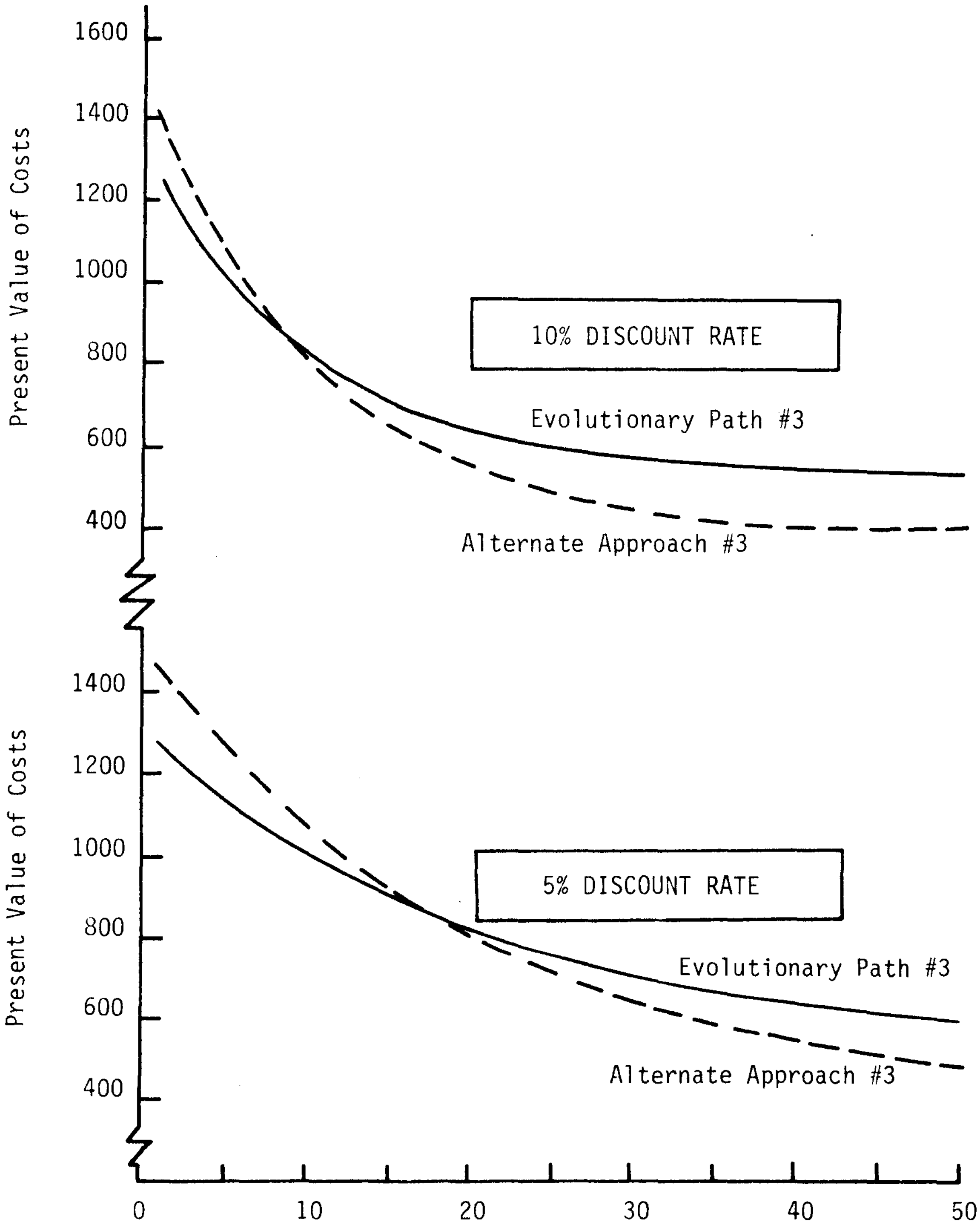

Figure 4: Present Value of Evolutionary Path #3 and Alternate Approach #3

COMPARISON OF TRANSITION CAPABILITIES

All the discussion of specific transition problems so far has pertained only to a wide guideway design (Evolutionary Paths #1 and #2). No concurrent bus operation can be conducted on a narrow guideway (Evolutionary Path #3) while it is being converted to another mode. However, the construction activities could be staged by segments of the narrow guideway so that buses could use portions of it during the initial transition process.

An analysis of specific operational problems that would be encountered during the transition was conducted for each evolutionary path. For the purposes of this analysis, the following two alternative transition techniques were assumed for Path #3 (narrow guideway):

- Path #3A -- Convert entire length of guideway concurrently, and
- Path #3B -- Convert half of the length of each corridor during the initial phase and the remainder during the final phase.

The impact of the transition period on various operational parameters was estimated for each evolutionary path so that their relative ease of transition could be compared. The parameters evaluated include the time required for each transition phase, bus capacity, average operational speed, and the disruption of other traffic in the corridor.

Time Required - Estimations of time required to construct portions of a transit system are inherently inaccurate because so many factors can delay construction. Despite these inherent inaccuracies, time estimates were developed for this process. Hopefully, these estimates represent the minimum realistic time required to accomplish the various construction activities.

The CBD portion of the system will have to be constructed from scratch. The Lindenwold Line was placed into service only three years after the initial construction work began, while more than six years elapsed between the beginning of construction and the initiation of service on the Washington, D. C. Metro. The problems associated with the subway segments of this system in the CBD will probably be more similar to those encountered on the Metro system than on the Lindenwold system. So a realistic time estimate for constructing the CBD portion of the system is probably in the range of five to six years.

Construction activities in the CBD, however, will not interfere with the bus operations on the existing guideways. Thus, the true transition period will be the time required to convert the existing guideways to RRT or AGT operation. If this estimated time is shorter than that required to build the CBD subway segments, then the construction of the CBD portions should precede the conversion work by an appropriate lead time.

Some typical times specified in contracts from BART and Metro for certain construction activities that will be included in the initial transition period are as follows:

- Trackwork -- 16 to 18 months,
- Power System -- 21 to 24 months,
- Control System -- 18 to 24 months, and
- Stations -- 16 to 18 months.

If these activities are staggered just enough to keep the various contractors out of each other's way, then the total package of work included in the initial transition phase could possibly be accomplished in 24 months. However, some additional time will probably be required because of the need to schedule certain construction activities around the bus operations. Thus, the estimated time required for accomplishing the initial transition phase on Evolutionary Paths #1 and #2 is 30 months.

The final transition period for Evolutionary Path #1 and #2 involves some minor construction work (which can probably be accomplished in six months) and a period for testing and debugging the system. The time needed for debugging is directly related to the degree of reliance on proven technology versus advanced technology. The Lindenwold Line used only proven technology and their testing/debugging was accomplished in a few months. BART, on the other hand, is still debugging after several years. For the purposes of this analysis, a testing/debugging period of 12 months was assumed for the RRT system (Path #2) and 18 months for the AGT system (Path #1).

Evolutionary Path #3A (narrow guideway, BRT → RRT) does not involve concurrent operation of buses on the guideway during transition, so the six months penalty was not added to the estimated time. Thus, the total estimated time for converting Path #3A to RRT is 42 months.

Evolutionary Path #3B is just like #3A except that half of the guideway will be converted to full RRT operation before the conversion process is started on the remaining half. Some time savings should accrue from the lesser amount of work; thus, the initial transition period is estimated at 36 months (rather than 42 months for Path #3A). The final transition period for Path #3B can probably be accomplished in only 30 months due to less time needed for testing/debugging.

Capacity - The capacity of a busway was calculated to be 940 buses per hour in each direction at an acceptable level of service; however, various factors will combine to reduce this capacity during the transition period. For the purposes of this study, it was assumed that carpools would be excluded from the transitway before any transition would accur. Thus, the capacity calculations need only concern bus operations.

For Evolutionary Paths #1 and #2 (wide guideways), buses will continue to use the shoulder of the guideway throughout the transition. During the initial transition period, the reduced width of roadway available for bus operation (10 feet instead of 12 feet) will result in a reduced capacity. The Highway Capacity Manual (6) shows a capacity factor of 0.74 for a two-lane roadway with obstructions on either side; thus, the capacity during the initial transition period is estimated to be 940 x 0.74 = 696 ≈ 700 buses per hour.

During the final transition periods of Evolutionary Paths #1 and #2, all buses will exit the guideway at each station and travel through two intersections. Even though it is assumed that the intersecting cross streets will be collector streets rather than major arterials, it is likely that traffic signals will be needed during the final period. These intersections will probably become the bottleneck that limits the capacity of bus operation. Assuming that each intersection will have a short two-lane approach, and that the signal timing can favor the bus flow (60 percent green time), then the capacity of these intersections will be between 500 and 600 buses per hour depending upon the utilization of the added approach lane.

For Evolutionary Path #3, the buses will have to operate on facilities other than the guideway during the transition. If a freeway lane can be devoted to bus operations for each corridor, then the capacity during transition will be approximately the same as for the other paths (≈ 700 buses/hour). However, if the buses must use a lane of a surface arterial street, the capacity will be reduced to only 330 buses per hour.[1]

Speed - During normal busway operations, average service speeds of 50 mph should be achievable with maximum speeds of 55 mph on the guideway. However, the maximum speed during transition will probably need to be limited to 45 mph

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[1] From Highway Capacity Manual (6): $\frac{\text{1100 autos/hour of green}}{\text{1.5 autos/bus}} \times 0.45$ (percent of green) = 330 buses/hour.

for safety reasons; therefore, the average service speed will be 40 mph for shoulder operation. Delays encountered at intersections during the final transition period will further reduce the average service speed to approximately 35 mph (assuming a 30-second delay for each station) for Evolutionary Paths #1 and #2. If the buses have to use a lane of a surface arterial street during transitions for Evolutionary Path #3, the average service speed will be reduced to 20 mph.

Disruption of Corridor Traffic - Another problem that needs to be considered is the disruption to normal corridor traffic that will be caused by bus operations during the transition. Detailed studies of specific corridors will be required to assess this impact in terms of delay time, capacity, speed, etc. For the purpose of this study, however, the relative severity of the disruption that will be caused by each path can probably be evaluated by considering the percentage of the corridor length that will be affected and the duration of the transition period. The disruption factor used to compare the relative impact of different paths is the product of these two parameters (percentage of corridor length x months of duration).

Comparison of Paths - The total focus of this study concerns the ability of a transitway design to accommodate the transition from bus operation to another technology. Hence, it seems that a comparison of the transition period for each Evolutionary Path is appropriate. Such a comparison is presented in Tables 6 and 7. An inspection of the information contained in these tables reveals a clear advantage for Evolutionary Paths #1 and #2 (using a wide guideway) over Evolutionary Path #3 (narrow guideway).

Table 6: Comparison of Bus Operations During Transition

Transition Parameter	Evolutionary Path Number			
	1	2	3A	3B
Initial Transition Period				
Time Required, months	30	30	42	36
Bus Capacity, veh/hr	700	700	330	330
Average Service Speed, mph	40	40	20	30
Final Transition Period				
Time Required, months	24	18	--	30
Bus Capacity, veh/hr	500	500	--	330
Average Service Speed, mph	35	35	--	20

Notes: For Evolutionary Paths #1 and #2, initial period operation is entirely on guideway, and final period operation uses ramps to bypass station construction.

For Evolutionary Path #3A, entire operation is on arterial streets.

For Evolutionary Path #3B, initial period operation is half on guideway and half on streets, while final period operation is entirely on streets.

Table 7: Relative Disruption to Surface Traffic During Transition

Disruption Parameter	Evolutionary Path Number			
	1	2	3A	3B
Percentage of Transit Trip that Interferes with Surface Street Traffic	10	10	100	50/100
Length of Disruptions, months	24	18	42	36/30
Disruption Factor	240	180	4200	4800

Notes: Length of disruption is only that portion of the total transition period that involves operation on local streets.

The disruption factor is the multiple of the other two factors.

CONCLUDING REMARKS

The most significant findings of this design study are that an evolutionary design which accommodates continuous bus operation during transition is feasible and that the design approach is strikingly simple. The key to the whole approach is the use of a wide guideway.

Not only does the wider guideway enable buses to continue to use the transitway during the transition, but the resulting shoulders also provide significant benefits to the final operational phase (either AGT or RRT). Indeed, the only features incorporated in the initial design for Evolutionary Path #1 (Bus/carpool → BRT → AGT) that are not needed in the final phase are the entry and exit ramps and the passenger shelters located in the park-and-ride lots. It may even be desirable to retain the entry and exit ramps at a few locations to provide access to the guideway for self-propelled maintenance and emergency vehicles.

The design approach shown for Evolutionary Path #2 (Bus/carpool → BRT → RRT) could even be considered a "universal guideway" design. It is designed with the structural capability to accommodate any mode (BRT, LRT, AGT, or RRT) and the decision concerning the specific mode could be postponed until conditions developed that stimulated a need to change modes. However, the increased structural capability is a costly feature that might never be used.

It seems that several additional questions need to be addressed before a decision can be made concerning the desirability of building an evolutionary design rather than a busway. These questions include the following.

1. What is the probability that a transition in modes will ever be needed?
2. What are the penalties associated with building an evolutionary design and then never making a transition?

3. What are the risks associated with not having an evolutionary design if a change in mode does become desirable?
4. What other factors should be considered?

These questions will be addressed in the final report for this project.

REFERENCES

1. Bus Rapid Transit Options for Densely Developed Areas. Prepared for U.S. Department of Transportation by Wilbur Smith and Associates, February 1975.

2. U.S. Department of Transportation, Characteristics of Urban Transportation Systems, May 1974.

3. Rail Transit System Cost Study. Prepared for Urban Mass Transportation Administration by Thomas K. Dyer, Inc., March, 1977.

4, Pittsbury-Antioch, Bart Extension Project, Final Draft. Prepared by Parsons-Brinckerhoff-Tudor-Bechtel with Wilbur Smith and Associates and Ingmire-Patri for Bay Area Rapid Transit District, January, 1975.

5. Transit Hardware, Low Capital Alternatives, and UMTA Research, Development, and Demonstration Programs. Prepared for North Central Texas Council of Governments by Public Transportation Center, University of Texas at Arlington, August 1975.

6. Highway Capacity Manual, Highway Research Board, Special Report 87, 1965.