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Transit and Urban Form

COMMUTER AND LIGHT RAIL TRANSIT CORRIDORS: THE LAND USE CONNECTION

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Parsons Brinckerhoff Quade & Douglas, Inc.
Dr. Robert Cervero
Howard/Stein-Hudson Associates, Inc.
Jeffrey Zupan

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Jeffrey M. Zupan is the principal author of this report.

David Kerr of Parsons Brinckerhoff did the statistical analysis for the demand models and is the principal author of Appendix B comparing the United States and BART models with Chicago transit.

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Phil R. Smelley, T. Brent Baker, and Susan K. Serres of Parsons Brinckerhoff developed the cost models and are the principal authors of Appendix E on the cost models.

Robert Cervero, University of California at Berkeley, is the principal author of Appendix A on the influence of land use on ridership for BART.

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EXECUTIVE SUMMARY

The purpose of the research is to provide guidance as to the land use characteristics in a corridor that can support new fixed-guideway transit services cost-effectively. It is postulated that land use characteristics in a corridor are a significant factor that drive the demand for transit service and, therefore, the value and effectiveness of such services. The research supports making the case for fixed-guideway transit where it is cost-effective and conversely lessening the demand for expensive fixed-guideway services where land use characteristics cannot support them. The research also makes it possible to suggest the nature of the changes in land use that could support transit.

Currently, many metropolitan areas in the nation are considering new rail transit lines. Taken together, if all the proposals were implemented, it would add 2,500 miles of new transit lines and increase the extent of such systems by 65 percent. Because most of these proposals are for light rail or commuter rail services, the focus of this research is on those two modes. Twenty-nine metropolitan areas are seriously entertaining new or expanded light rail services and eighteen are considering commuter rail. Heavy rail is only being proposed as expansions in cities where that mode already exists.

The proposals for additional rail transit are being advanced despite the long term and continued trend away from the core of our metropolitan areas and toward suburban development that tends to work against transit. The attention to new transit lines is motivated by a number of factors including:

- Concerns about the negative impact of auto-oriented sprawl;
- Desires to reduce air pollution and energy consumption;
- Interest in rebuilding urban communities;
- Need to provide access and mobility to those without autos; and the
- Desire to save the costs and avoid the impacts of constructing new or widened roads.

APPROACHES TO DEMAND AND COST MODELING

The approach taken in this research is to first define, as a function of land use in a corridor, the likely light rail or commuter rail ridership generated in that corridor. Once these ridership levels are determined they are matched against the costs — both operating and capital — necessary to meet the demands for the service. A series of hypothetical but realistic corridors are constructed, with varying land use patterns and intensities, and then light rail and commuter rail lines are overlaid on the corridors to determine the ridership and costs generated by the relationships developed in this research.

The analysis focused solely on radial corridors emanating from the Central Business Districts (CBD), since they are the only corridors that exist today. It is not possible to develop demand relationship for non-radial corridors in the absence of such data.

On the demand side, a generic model is developed to account for the major factors that generate transit travel in a corridor, including land use, its intensity, and location. Two models, one that estimates daily ridership boarding at a light rail station and the other at a commuter rail station are developed. Data from 19 lines in 11 metropolitan areas with a total of 261 stations are used for the light rail model. Data from 47 lines in six metropolitan areas with a total of 550 stations are used for the commuter rail model. The models bypass the usual four-step travel demand modeling process with a simplified approach that estimates transit demand directly, incorporating trip generation, mode choice, trip distribution, and trip assignment features. The models consider the number of people living near the station, the characteristic of that population such as income and auto ownership, the size and density of employment in the CBD which the line serves, the distance and travel time between the station and the CBD, the availability of access mode services such as feeder bus and parking, and the impact of competing rail services nearby, either on the same line or on parallel ones.

The results are two demand models, one for each mode that account for most, but not all, of the postulated factors. Table ES-1 summarizes the results. As expected population density near the station matters for both models, but because of collinearity problems, only employment density and not employment size could be included in the commuter rail model. Income shows up in the commuter rail equation, with higher incomes producing more trips for this relatively expensive mode. Access mode availability shows a strong effect for both models, with feeder bus availability more important for light rail and parking availability more important for commuter rail. The distance to the CBD also is an important variable with light rail riders dwindling farther from the core, but for commuter rail the distance function is more complicated, first growing with distance and then dropping beyond about 35 miles. Competing service entered the picture in the light rail equation where the competition from a nearby station on the same line dampened ridership.

The cost models are developed from data from twelve light rail and eleven commuter rail systems and identify the factors that contribute to operating and capital costs. Operating costs are largely a function of labor requirements, which are, in turn, a function of the extent of the system, how intensively it is used and indirectly, and the ridership on the line which drives the size of the vehicle fleet that must be maintained. In the relationships, annual vehicle-hours, annual vehicle-miles, the size of the vehicle fleet, and track-miles figure prominently in the operating cost relationships for both modes. Capital costs were developed using contract costs. As expected, the operating costs show a stronger relationship with the use of the system and the capital costs show a stronger one with the extent of the system. Taken together, the costs are indirectly a function of ridership, and thus, indirectly a function of land use.

It is also helpful to define the range of peak hour riders for which each of these two rail modes would logically operate. The physical characteristics of a line put an upper limit on ridership levels. For light rail this translates into daily one-way boardings of 46,000. For commuter rail its 80,000. Similarly, below some ridership level the amount of peak hour service that could be offered is too low to be a reasonably attractive service. For light rail this translates into 2,700 daily one-way boardings; for commuter rail it is 3,600.

Table ES-1. Summary of Factors Influencing Light Rail and Commuter Rail Ridership

Variable	Light Rail	Commuter Rail
Employment	CBD jobs CBD job density **CBD jobs & job density**	CBD jobs **CBD job density** CBD jobs & job density
Population	**density within 2 miles** density within 1/2 mile	**density within 2 miles** density within 1/2 mile
Access	**some feeder bus** **parking available**	**some feeder bus** **parking available**
Distance to CBD	**log linear**[1] quadratic	log linear **quadratic**[2]
Competition	**nearest station** nearby line	nearest station nearby line
Income	income	**income**
Terminal?	**yes**	yes
CBD Terminal Distance	not applicable	no

The table lists all factors that were considered in the analysis. **Bold** type indicates the variables that are statistically significant in the best-fitting models.

[1] For light rail, boardings decrease with distance from the CBD following a downward sloping curve or log-linear function.
[2] For commuter rail, boardings increase with distance from the CBD up to about 35 miles from the CBD and then decline with increasing distance as modeling by a quadratic function.

An analysis of hypothetical light rail lines shows that there is a significant range of conditions for large cities where light rail systems are likely to be inappropriate, particularly where CBD jobs are in excess of 250,000. In these larger CBDs ridership would exceed manageable levels. At the low end of the light rail ridership spectrum, even CBDs of only 25,000 jobs can support the service on ridership grounds.

FINDINGS

With the demand and cost models in hand, a series of hypothetical corridors are constructed to estimate the travel demand for them, and then the costs. For these corridors CBD employment and density, residential density gradients in the corridors, access mode availability, and rail line length are varied. For each of these corridors the number of riders that would board trains on an average weekday are estimated.

Light Rail Ridership Grows with CBD Size and Density and with Residential Density

For light rail corridors the most striking feature is the exponential growth that occurs as both CBD employment and employment density increases. Higher ridership levels also occur with higher residential density gradients with the most substantial increases occurring with longer lines. With an increased length, ridership grows, but on a diminishing per mile basis. The availability of feeder buses impacts ridership significantly too. When this service is provided to virtually all of the stations, ridership grows by about 15 percent compared to a situation where only about half the stations have feeder bus available. Parking availability has a much weaker effect on light rail ridership.

Commuter Rail Service Requires Dense CBDs but can Operate in Low Density Residential Areas

Commuter rail ridership also grows significantly with CBD size, but does not grow in the same exponential fashion as light rail. CBD employment density also has a lesser effect than it does for light rail. Residential density appears to have little effect on commuter rail ridership because of growing ridership with distance to the CBD (up to about 35 miles) even as residential density falls, and because of the offsetting effects of income. (Higher incomes associated with lower densities produce more, not less riders.) The net effect is that for commuter rail, unlike light rail, residential density in the area of the stations is largely irrelevant to ridership. Only in the limited situations where higher densities are associated with higher incomes within reasonable commuting distance by commuter rail — say 40 miles — will the positive impact of higher residential density on commuter rail be felt. For commuter rail the roles of the two access modes are reversed. Parking availability has a larger impact than does feeder buses.

These findings suggest that low density areas can support commuter rail ridership by bringing riders from a large area, especially if parking and some feeder bus service is provided to offset the small numbers within walking distances to stations. Of course, site specific situations and costs may not always make it possible or desirable to provide parking and bus feeders at all stations.

Light Rail Costs Rise with Ridership and Line Length. Commuter Rail Costs Vary with CBD Size and Line Length.

Turning to cost consideration it is hardly surprising that light rail costs the most when the ridership is high and the line is long. Higher CBD employment drives the growth in ridership, which, in turn, requires more vehicles and more workers to operate and maintain them, increasing operating costs. The line length, meanwhile adds to the operating cost too, with more riders and with more workers needed to maintain the right-of-way. Similarly, the higher ridership associated with higher residential densities also drives up costs.

For commuter rail, operating costs are high when the CBD is large and the line is long, but capital costs are less sensitive to CBD employment and more sensitive to the length of the line.

While there is value in understanding the factors that separately affect both operating and capital costs — the funding sources are usually different — in this analysis the two are combined by added the annual amount necessary to replace the capital to the operating costs. This is referred to as the total cost.

The analysis of hypothetical commuter rail lines suggests that commuter rail, at least from a ridership perspective, requires large CBDs and relatively long lines. It remains to be seen what happens when cost criteria are added to the mix.

Light Rail Works Best in Larger Cities with Denser Corridors. Commuter Rail Works Best with Dense CBDs.

Measures of cost-efficiency and effectiveness are next calculated for the hypothetical light rail lines. Cost-efficiency is measured by total cost (annual operating cost plus depreciation) divided by the annual-vehicle miles. Effectiveness is measured by daily passenger-miles per line-mile.

Collectively, for light rail the measures of cost-efficiency and effectiveness each indicate a strong positive relationship with CBD employment size and residential density. A weaker but significant relationship also occurs for CBD employment density and for line length. This suggests that larger cities with higher density corridors will work best for light rail. But as noted earlier at very high demand levels for larger CBDs, the ridership attracted to light rail may not be practically handled and a higher capacity heavy rail may be needed. At the lower end of the land use spectrum, cost-efficiency and effectiveness may suffer, but increases in residential density might make up for smaller CBDs, and conversely more development in the CBD could allow for effective and efficient light rail without any significant increase in residential densities. The importance of both the size and density of CBDs suggest that corridors that do not pass through or terminate in a CBD would be harder pressed to be cost-effective.

Within the range of feasible commuter rail corridors much more travel will be accommodated on lines to larger and more dense CBDs. But there is a cost-efficiency trade-off. The larger and more dense CBDs will cost more on a per vehicle-mile basis.

That can be mitigated by making the line longer. But that too involves a trade-off, since longer lines will cost more to construct.

The analysis described in this report, summarized in Table ES-2, suggests strongly that light rail and commuter rail transit performs better when there is a large CBD. However, light rail may not work at all when CBDs get too large since ridership may outstrip the modes carrying capacity. For commuter rail, the larger CBDs produce more effective services, but are slightly less cost-efficient.

The density of the CBD is particularly important for commuter rail, probably because there is usually only one terminal station and lower density CBDs may put some jobs beyond easy reach of the terminal station. Light rail, in contrast, is less affected by the density of the CBD since there are likely to be multiple stations to serve lower density CBDs.

Residential density itself matters for light rail and commuter rail but, in the latter case, density is confounded by the effect of income, since commuter rail's higher fares attracts more riders with higher incomes, who also tend to live at lower densities.

The length of the rail line assumes some importance for both light rail and for commuter rail. Longer light rail lines are both slightly more cost-efficient and effective. But the effects diminish with length. Commuter rail lines are much more cost-efficient when they are longer, but their effectiveness declines beyond 50 miles. At short distances there often are not enough riders to justify even minimal service on commuter rail.

The availability of access modes can help to achieve higher performance levels, all else being equal; feeder buses more strongly affects light rail and parking more strongly affects commuter rail.

Light Rail and Commuter Rail Serve Different Markets.

Among the more interesting findings in this research is the distinctly different characteristics of light rail and commuter rail. It is clear that they serve different markets and different land uses patterns. Indeed, there are more dissimilarities than similarities. This does not imply that in any one metropolitan area they both may not have a niche, only that they have different niches.

Table ES-2. Summary of Findings on Cost Efficiency and Effectiveness for Hypothetical Rail Corridors

Factor	Cost Efficiency (total cost/vehicle mile)	Effectiveness (passenger miles/line miles)
Light Rail		
Residential density gradient	highly positive	highly positive
CBD employment numbers	moderately negative at high CBD job levels rail may not be feasible	highly positive
CBD employment density	slightly positive	moderately positive greater impact for larger CBDs
Feeder bus	unclear	highly positive
Parking availability	unclear (site-specific)	moderately positive
Line length	slightly positive	slightly positive
Commuter Rail		
Residential density gradient	not significant	not significant
CBD employment	slightly negative, for smaller CBDs may have insufficient riders, especially for shorter line lengths	highly positive
CBD employment density	highly positive	highly positive
Feeder bus	unclear	moderately positive
Parking availability	unclear (site-specific)	highly positive
Line length	strongly positive, insufficient riders for shorter lengths	varies, best at 50-mile length

OTHER CONSIDERATIONS FOR EVALUATING SPECIFIC PROPOSALS

Not accounted for here but worthy of serious exploration is a fuller consideration of costs, including those saved as a result of other modes not used, if the rail line is put in place. To accomplish this is it would desirable to assign the rail ridership to the modes from which riders would be diverted — auto and bus — and estimate the appropriate savings in operating, capital and full environmental costs. Beyond that, the application of the full costs of both transit and highway modes can balance the burden that rail transit must now bear in proving its value. Also, not accounted for is the sizable ridership that might be found traveling to nonresidential clusters at intermediate stops or at the non-CBD terminal. In a number of places, particularly for light rail lines this has proved substantial. The relationships in this report can be applied in such situations.

The need of planners to have specific land use thresholds for support of transit is understood. In fact, the earlier works by Pushkarev and his colleagues provided such thresholds. But these works were also clear to caution the reader that such thresholds were no substitute for careful site-specific analysis. The thresholds were only a guide to give planners a sense of whether there is a reasonable possibility for transit to work in different settings. Such a guide is still needed today, and the earlier works can still serve that purpose, but now with the added caveat created by the passage of some 15 to 20 years. In this report, land use specific thresholds are not given. Rather, further guidance of the expected effectiveness and efficiency of fixed rail systems as a function of land use is provided to help put "meat on the bones" to assist in the consideration of so many plans now being put forth.

Finally, this effort should not be viewed as a substitute for a careful examination of all transportation alternatives in all types of corridors including those that do not end in the CBD, accounting for site-specific conditions and preferences. Rather, it should be seen as a means to understand the role that land uses in a corridor play in determining costs. Further, it makes clear the need to integrate transit planning with land use planning at the earliest possible stage, a finding that is reinforced in the case studies prepared for another report of this project, <u>Public Policy and Transit Oriented Development: Six International Case Studies</u>.

1.0 INTRODUCTION

The purpose of this task is to provide guidance on the land use characteristics that support new fixed-guideway transit services in a corridor. This work has as its antecedent the research conducted in the 1970s by Pushkarev and Zupan. Public Transportation and Land Use Policy (1977) established land use thresholds necessary to support transit in a cost-effective manner. That work had three motivations: 1) to define the land use patterns and densities on the metropolitan landscape where transit made economic good sense, thereby making the case for transit despite high costs and public subsidies; 2) to limit the investments in transit in those land use situations where it was difficult to support from a cost perspective; and 3) to suggest changes in land uses that could support increased transit services. Later, in Urban Rail in America (1980) Pushkarev, with Zupan and Cumella applied the demand relationships associated with land use variations established in the first book, developed five demand-based criteria and their thresholds to support rapid transit, light rail and automated guideway people-movers, and applied these thresholds to those major America metropolitan areas that did not have such facilities at that time.

In the intervening years, many metropolitan areas have considered new rapid transit, light rail or downtown people-movers. Many have gone ahead and built them and others, after much public debate, rejected these systems. Light rail, in particular, has enjoyed popularity, and many more continue to be proposed. In recent years, commuter rail services have been restored over sometimes long-abandoned rights-of-way, and others are proposed. Table 1 and Table 2 show the cities in the United States with light rail and commuter rail systems and indicate those areas where there are active proposals to extend the existing system or to initiate service.

There are currently 17 cities in the nation with light rail lines (exclusive of tourist type or other special purpose trolleys). Seven of these 17 are extending their systems with work under construction now, and all 17 are either planning or designing extensions. Also, at least 12 cities currently without light rail are in some stage of planning or design of light rail implementation. All together, there are 29 cities in the nation which either have light rail lines or are planning them, with new possibilities continually arising.

There are currently 10 cities in the nation with commuter rail systems. Of these, two have work under construction for extensions, and seven are either planning or designing extensions. At least eight cities currently without commuter rail are in some stage of planning or design of new systems. Eighteen cities in the nation either have commuter rail lines or are planning them.

Table 1. United States Light Rail Lines

In Operation		Under Construction	
Before 1970	**Since 1970**	**Extensions**	**New Cities**
Boston	Baltimore	Cleveland	
Cleveland	Buffalo	Dallas	
New Orleans	Dallas	Los Angeles	
Newark	Denver	Portland	
Philadelphia	Los Angeles	Sacramento	
San Francisco	Pittsburgh	San Diego	
	Portland	San Francisco	
	Sacramento		
	San Diego		
	San Jose		
	St. Louis		

In Design		Planning	
Extensions	**New Cities**	**Extensions**	**New Cities**
Baltimore	Chicago	Baltimore	Burlington, VT
Dallas	North Jersey	Boston	Columbus
Denver	New York	Buffalo	Detroit
Cleveland	Salt Lake City	Cleveland	Kansas City
Portland	San Juan	Dallas	Memphis
Sacramento		Los Angeles	Milwaukee
San Diego		Newark	Norfolk
		New Orleans	
		Pittsburgh	
		Portland	
		Sacramento	
		St. Louis	
		San Diego	
		San Francisco	
		San Jose	
		San Juan	

Source: Transit Fixed Guideway Inventory, American Public Transit Association, April 10, 1995

Note: Since APTA complied this data, the status of some systems have changed. For example, Philadelphia is now studying light rail extensions.

Table 2. United States Commuter Rail

In Operation		**Under Construction**	
Before 1970	**Since 1970**	**Extensions**	**New Cities**
Boston	Baltimore	Boston	Dallas
Chicago	Los Angeles	Los Angeles	San Diego
New York/New Jersey	Miami		
Long Island RR	Wash. (Va.)		
Metro North			
North Jersey			
Philadelphia			
San Francisco			
Washington			

In Design		**Planning**	
Extensions	**New Cities**	**Extensions**	**New Cities**
Baltimore	Dallas	Baltimore	Atlanta
Boston		Boston	Cincinnati
Chicago		Chicago	Cleveland
Miami		Dallas	Denver
San Francisco		Los Angeles	Hartford
		Miami	St. Louis
		NY (Metro North)	Seattle
		North Jersey	
		Philadelphia	

Source: Transit Fixed Guideway Inventory, American Public Transit Association, April 10, 1995

Note: Since APTA compiled this data, the status of some systems have changed. For example, San Diego's commuter rail began operating in February of 1995, and San Diego has another line in the planning stages.

Rapid transit (heavy rail) proposals for new or expanded lines are much less common than are light rail and commuter rail services. Of the thirteen systems in place today, ten are in construction, design, or planning of expansions, but there are no cities without heavy rail now seriously contemplating such systems. Table 3 compares the number of cities with each of the three modes — light rail, commuter rail and heavy rail systems — and planned expansions or new systems. Most telling are the number of miles that are involved in the planned expansion of existing lines or services in new cities. Light rail proposals, if all built, would add 166 percent to the mileage in the nation, commuter rail would add 65 percent, but heavy rail would add only 21 percent, none of it in cities without heavy rail now. It is for this reason that this study has decided to focus its attention on the light rail and commuter rail modes.

Table 3. Expansion Plans for Fixed Rail Transit Systems in the United States

Number of Cities

Mode	Existing	Expansions	New	Total (existing plus new)
Light Rail	17	16	12	29
Commuter Rail	10	7	8	18
Heavy Rail	12	10	1	13

Number of Miles

Mode	Existing	Expansions	New	Total	Potential Growth
Light Rail	305	456	49	810	166%
Commuter Rail	2,849	846	999	4,694	65%
Heavy Rail	689	147	0	836	21%
TOTAL	3,843	1,449	1,048	6,340	65%

Source: Transit Fixed Guideway Inventory, American Public Transit Association, April 10, 1995

Note: Totals do not include changes that occurred after APTA compiled this data.

Even while many new and expanded systems are being proposed, trends in our metropolitan areas are working against increased transit use. Over the last twenty years, auto ownership has increased rapidly, with many more households owning two or more autos, suburban job sites have increased at the expense of jobs in the cities, suburban activity centers serving many of the functions of the traditional downtowns have emerged, and attitudes towards subsidized transit have shifted.

Still, new services continue to be advanced in response to the desires to minimize some of the negative impacts of a more auto-dependent and sprawled development pattern. Transit is seen as a way to ease road congestion, to reduce air pollution, to consume less energy, to assist in rebuilding urban communities, to limit suburban sprawl, to provide mobility for those without autos, and to save the cost and impacts of new or widened roads. The desire for new transit services to meet these objectives naturally raises the issue of where and how best to provide cost-effective transit services. The aim of this report is to provide guidance on land use characteristics that most cost-effectively support such investments.

The need of planners to have specific land use thresholds for support of transit is understood. In fact, the earlier works by Pushkarev and his colleagues provided such thresholds. But these works were also clear to caution the reader that such thresholds were no substitute for careful site-specific analysis. The thresholds were only a guide to give planners a sense of whether there is a reasonable possibility for transit to work in different settings. Such a guide is still needed today, and the earlier works can still serve that purpose, but now with the added caveat created by the passage of some 15 to 20 years. In this report, land use specific thresholds are not given. Rather, further guidance of the expected effectiveness and efficiency of fixed rail systems as a function of land use is provided to help put "meat on the bones" to assist in the consideration of so many plans now being put forth.

1.1 REPORT ORGANIZATION

The report first addresses the questions of demand and then those of cost. In each case empirical data is used to develop a model and then this model is applied to hypothetical rail corridors. Section 2 provides introductory material on the approaches to this research. Section 3 presents the empirical demand analysis based on existing light rail and commuter rail systems in the United States. Section 4 gives ridership estimates for a variety of hypothetical light and commuter rail models using a series of graphs and discussion. Section 5 outlines the process of estimating the operational and capital costs of rail systems. (More details on the cost models are presented in an appendix). Section 6 estimates costs for the same hypothetical rail models used earlier and presents the results in graphs and discussion. Section 7 draws some conclusions about the relationships of land use and cost effective rail transit.

Appendices A and B present supplemental research that examines ridership on the three systems used for other topics in this project—the Bay Area Rapid Transit (BART) and the CTA heavy rail and Metra commuter rail in Chicago. Appendix A discusses several ridership models for BART. Appendix B compares the Chicago systems to the United States models developed in the main part of the report and the BART models in Appendix A.

Appendices C through F provide details to supplement the main report.

2.0 RESEARCH APPROACH AND HYPOTHESES

This research attempts first to define, as a function of land use in a corridor, the likely light rail or commuter rail ridership generated in that corridor. Once these ridership levels are determined they are matched against the costs — both operating and capital — necessary to meet the demands for the service.

A series of hypothetical but realistic light rail and commuter rail transit lines in corridors are constructed, varying land use patterns and intensities in the corridors as well as the characteristics of the transit line. From these hypothetical examples ridership and costs are estimated using relationships developed as part of this research.

To estimate demand, the standard four-step urban transportation demand technique, suitable in transportation studies of specific metropolitan areas, is much too elaborate to be used here, especially where data for many areas needs to be combined. Instead, a <u>generalized direct transit demand estimation method</u> is used, combining many of the elements of trip generation, trip distribution, modal choice and trip assignment — the four steps in the transportation planning process. Transit ridership is estimated directly for each station and summed for the line, using the premise that the overriding factors in determining transit ridership at a station are the **number of people** who reside in the area of the station who can easily reach the transit station, and the **number of jobs** located within the central business district where the line terminates. These variables provide for the trip generation element of the direct estimation method.

The likelihood of any one person residing in an area, traveling to a particular job concentration is a function of the **distance or travel time** between them. Thus, the distance or travel time can represent the trip distribution element of the direct estimation method.

The likelihood of the travelers between any points using transit is a function of the service provided by transit and by the alternative — the automobile. The availability of access to the station or line, measured by the availability of **connecting transit service** and the supply of **adequate parking**, adds to the likelihood that people living in an area will use transit. The **population density** of the residential area and of the **job concentration** also affects the modal share. Higher **residential densities** associated with lower **incomes** and, consequently lower **auto ownership**, generally producing a higher share of trips by transit, and higher **job concentrations** associated with higher parking costs and more congested highway traffic reducing the attractiveness of the automobile, while simultaneously boosting the likelihood of transit use. These factors can be used to account for the mode choice portion of the generalized demand model. Finally, the choice a particular transit station to board, given the decision to use transit can be a function of the **distance to other transit stations and to competing transit lines**. Data representing each of the factors highlighted in the text were collected to build a generalized transit trip demand model. This model estimates the number of riders boarding a station based on the land use near the station the location of the station relative to the major Central Business District attractor of trips, the employment characteristics of that CBD, the access mode characteristics of the station and the presence of competing line-haul transit modes.

It is hypothesized that for light rail and the commuter rail considered separately, a station level demand model can be created that shows a positive relationship with demand for the following factors

Residential density near the station
Employment density in the CBD
Number of employees in the CBD
Presence of feeder bus services to the station
Presence of parking at the station

Distance from the station to the CBD
Whether station is the outermost station on the line

Factors that are hypothesized to have a negative effect on demand are:

Presence of nearly competing line-haul transit
Closeness of next nearest station on the line
Income of the population near the station

The cost of providing transit service includes both operating and capital costs. Operating costs are largely a function of labor requirements, which are, in turn, a function of the extent of the system, how intensively it is used and the indirectly, the ridership on the line which drives the size of the vehicle fleet that must be maintained. To determine operating costs and labor requirements for the light rail services, a set of cost models is developed from data collected from existing properties in North America. The operating cost models combines four major components of operating costs related to the number of workers assigned to those components — maintenance-of-way, vehicle maintenance, vehicle operations, and administration, and adds a fifth cost category to account for non-labor costs. Cost per worker data is then applied, enabling the calculation of operating costs.

The capital cost component of the life cycle costs of new rail lines is determined by examining recent contract costs for light rail and commuter rail lines. These are collected to try to differentiate line, station, and yard costs, wherever possible and to differentiate capital costs by right-of-way type (at grade, cut or fill, underground, elevated). For light rail the focus is on determining the physical characteristics of the new rail infrastructure and their costs. For commuter rail the focus is on upgrading existing railroad lines for commuter rail service. Once this is accomplished, average values are determined on a track-mile or line-mile basis, and on a per station basis, stratified by right-of-way type. Added to this is the cost of rolling stock using the fleet size determined for each of the hypothesized transit lines. Capital costs for each hypothesized transit line are then combined with operating cost estimates and brought to a common year, adjusting for inflation, and life cycle costs for each hypothesized transit line is determined.

Once the station demand and cost models are in place they are applied to a series of hypothetical, yet plausible corridors, incorporating the characteristics of land use that are found in the demand models to be most relevant, as well as the other variables that describe the transit line, such as line length and access modes. The outgrowth of this application is a series of curves that describe the lines effectiveness and efficiency in land use terms.

The analysis focused solely on radial corridors emanating from the Central Business Districts, since they are the only corridors that exist today. It was not possible to develop demand relationships for non-radial corridors in the absence of such data.

3.0 DEMAND ANALYSIS

3.1 DATA SOURCES

To develop the generalized direct transit demand estimation model, attempts were made to collect data from all systems in North America with light rail and commuter rail services, with the exception of the New York region. Because there are now numerous fixed guideway systems in operation with substantial empirical data available, there is a substantial pool of lines in varying settings from which data can be drawn for this research.

All of the United States cities with (non-tourist) light rail and commuter rail were contacted, first with letters and then with follow-up phone calls. The study team requested data on boardings and alightings by station and by line, for daily, peak period and peak hour, by direction. Fourteen light rail systems and eight commuter rail systems provided station level ridership data. Some could provide ridership data only on a daily basis rather than by the time of day and direction we requested. Table 4 shows the cities for which ridership data was successfully collected for the demand analysis. The complete list of light rail lines and commuter rail lines for which station data was collected is included in Appendix C.[3]

Table 4 shows the database used in the analysis includes 19 light rail lines in 11 cities. These lines have a total of 261 non-CBD stations and total daily boardings of 236,224 persons. The database also includes 47 commuter rail lines in six cities. These lines have a total of 550 stations and total daily boardings of 224 to 484 persons. Only stations outside the CBD are included in the analysis. Therefore, line length and station numbers are less than the total for each city.

The light rail systems for which data was collected comprise 159 miles of the 305 miles of light rail operated in the United States. The commuter rail data covers about half of the national mileage 1,267 miles of 2,849. Together, the 811 stations board 460,000 riders per day.

Five types of data were assembled for these stations:

1) Station identification information
2) Station ridership information
3) Transportation service characteristics
4) Population characteristics near station
5) CBD employment information

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[3] Three of the light rail systems are in Canada-Calgary, Edmonton, and Toronto. They were not included in the analysis because comparable employment and demographic data could not be obtained. Likewise, the commuter rail system in Toronto was dropped. In addition, Miami's commuter rail was deleted because it operates more like an intercity line than a CBD focused commuter rail.

A full description of the variables considered, any difficulties encountered, or data limitations are described in Appendix D.

3.2 RELATIONSHIPS AMONG VARIABLES

Table 5 lists the mean, median, 10th percentile and 90th percentile values for some of the key variables used in the analyses. These data suggest some interesting contrasts for the two modes and helps define the differences between them.

- Average ridership per station is almost double for light rail stations what it is for commuter rail (910 versus 470).

- Population densities associated with light rail stations are considerably higher than for commuter rail stations, using either the two-mile or 0.5-mile commutershed measure. Ninety percent of all light rail stations have population densities of at least 4.5 people per acre in the two miles surrounding the station. The comparable commuter rail density is only 1.8 people per acre.

- Automobile ownership and income are higher for the commuter rail stations.

- The CBD employment size and density are both considerably higher for the commuter rail stations. Employment size for the commuter rail observations are almost double the light rail observations and employment density is four times greater for commuter rail.

- Travel times to the CBD are 50 percent greater for commuter rail and distances are three times as long. This translates into an average speed for commuter rail of almost double that of light rail.

- The nearest station, a measure similar to average station spacing, averages two miles for commuter rail, but only 0.54 miles for light rail.

- Peak hour frequency is much higher for light rail with an average of almost eight trains per hour, while commuter rail is less than three per peak hour.

- Only one-third of the light rail stations have significant parking, but 90 percent of the commuter rail stations do. More than half of the stations — 61 percent for light rail and 52 percent for commuter rail — have some bus service. Neither mode have many stations with nearby competing rail services.

In short, commuter rail provides service to lower residential densities with high incomes further from the CBD. The core areas they serve are larger. The service offered by light rail is more frequent, but slower with less parking available. Light rail serves smaller CBDs from higher density residential areas with lower incomes closer to the core. Light rail's closer station spacing (by a factor of almost four) and higher ridership per station (by a factor of almost two) indicates that on a per mile of route basis light rail attracts about eight times the riders of commuter rail.

Table 4. Station Database Summary

Light Rail

City	Number of Lines	Number of Stations	Length (miles)	Daily Boardings
Baltimore	2	16	15.6	10,003
Boston	4	55	17.1	77,281
Buffalo	1	8	4.6	14,440
Cleveland	3	28	10.9	5,340
Los Angeles	1	18	19.0	28,360
Philadelphia	2	49	11.8	4,829
Pittsburgh	2	20	19.9	28,081
Portland	1	19	13.6	14,460
Sacramento	2	16	10.9	11,870
San Diego	2	23	27.4	30,536
St. Louis	1	9	8.6	11,024
TOTAL	19	261	159.4	236,224

Notes
Number of lines counted from CBD out.
Mileage only for portion of line outside the CBD.
Boardings per station = 905
Boardings per mile = 1,482

Commuter Rail

City	Number of Lines	Number of Stations	Length (miles)	Daily Boardings
Boston	11	97	219	42,617
Chicago	14	199	343	61,110
Los Angeles	5	39	286	9,771
Philadelphia	13	146	179	42,536
San Francisco	1	31	75	15,073
Washington	3	38	165	10,760
TOTAL	47	550	1,267	224,484

Notes
Number of lines counted from CBD out.
Mileage only for portion of line outside the CBD.
24 stations, 23 from Philadelphia and one from Los Angeles were later dropped because income data was missing.
Boardings per station = 408
Boardings per mile = 177
Source: Compile by authors from data provided by transit operators.
Note: The data in this table refers to the portions of rail line found outside the CBD, rather than to the entire line.

Table 5. Summary Statistics of Key Variables

Continuous Variables	Light Rail (N = 261)				Commuter Rail (N = 526)			
	Mean	Median	10th Percentile	90th Percentile	Mean	Median	10th Percentile	90th Percentile
Total daily boardings	910	630	50	1,900	470	310	100	1000
Population density (2 mile radius)	12	11	4.5	22	8.2	6.5	1.8	17
Population density (0.5 mile radius)	15	9.7	3.5	31	9.4	7.4	2.7	19
Number of cars per household	1.4	1.4	0.95	1.8	1.7	1.7	1.1	2.0
Average household income ($1,000s)	35	34	19	50	43	42	26	59
Number of CBD jobs (1,000s)	160	120	67	250	310	320	210	420
CBD employees per acre	100	61	27	240	220	240	130	320
Minutes to CBD	26	24	14	40	39	34	18	66
Miles to CBD	7.3	6.5	2.8	12	20	16	7.1	38
Miles to nearest station	0.54	0.40	0.15	1.1	2.0	1.2	0.50	4.6
Number of inbound trains in AM peak	7.7	7.0	4.0	12	2.7	3.0	1.0	4.0
Number of daily in bound trains	93	86	55	150	18	20	4	30
Dummy Variables		**Yes**	**No**			**Yes**	**No**	
Terminal station		8%	92%			8%	92%	
Parking present		32%	68%			90%	10%	
Competing service (nearby lines)		12%	88%			8%	92%	
Feeder bus		52%	48%			61%	39%	

Scatterplots were created to relate the boardings by station to the independent variables. Two of the more interesting ones are shown. In Figure 1 distance to the CBD is plotted against light rail station boardings. It would appear that the relationship is rather weak, and indeed the simple correlation is only -0.225 in the log-log form. Commuter rail shows a more obvious relationship in Figure 2. A parabolic function appears with boardings raising with distance until about 35 miles, with a rapid drop-off thereafter.

The simple correlation coefficient matrix for 261 light rail stations is shown in Table 6. Among the potential independent variables, the logarithms of distance to the next station, daily service frequency, and the dummy variable for some bus service, have the strongest correlations with the dependent variable, total daily boardings.

Among potential independent variables the simple correlations of some variable pairs are of interest. The availability of parking at a station is positively correlated with distance to the CBD and negatively with residential density. Stations farther out are generally in areas of lower density where parking is more easily provided. Distance to the nearest station is positively correlated with parking and feeder bus availability, meaning that where stations are close together there is less likelihood of needing either parking or feeder buses, since more riders can walk to stations. CBD employment and employment density are strongly negatively correlated with distance to the nearest station, suggesting that in the bigger cities with larger downtowns the light rail lines have stations farther apart, perhaps because the attraction of jobs in the CBD is enough of an incentive to use modes other than walking to reach the stations.

Similarly, the simple correlation coefficient matrix for the 526 commuter rail stations is shown in Table 7. Measures of parking and the frequency of train service are most strongly correlated with the dependent variable of total daily boardings.

Here again some of the simple correlations among variables is instructive. The correlation between the distance to the CBD and the distance to the nearest station is highly positive; stations are closest together nearer to the CBD. Residential density is negatively correlated with distance to the CBD and with income, as is the case with the light rail data set.

A number of features of the initial modeling resulted in improvements to the approach and the variables used. These center around the following topics:

- Service variables
- Distance to CBD
- Employment density and employment size
- Population density
- Distance from CBD commuter rail terminal to center of CBD
- Terminal station

**Figure 1.
Light Rail Station Boardings
by Distance to the CBD**

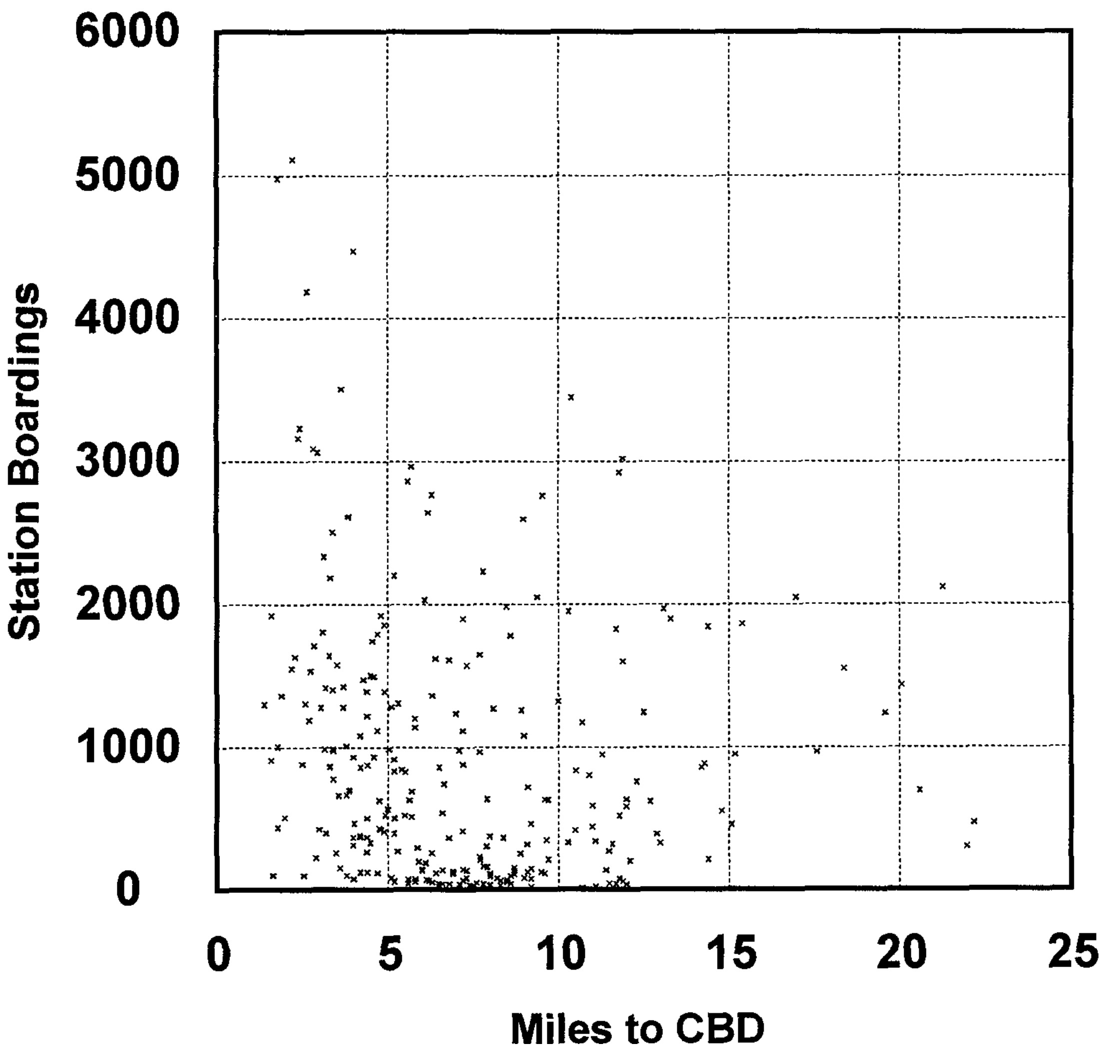

Figure 2.
Commuter Rail Station Boardings
by Distance to the CBD

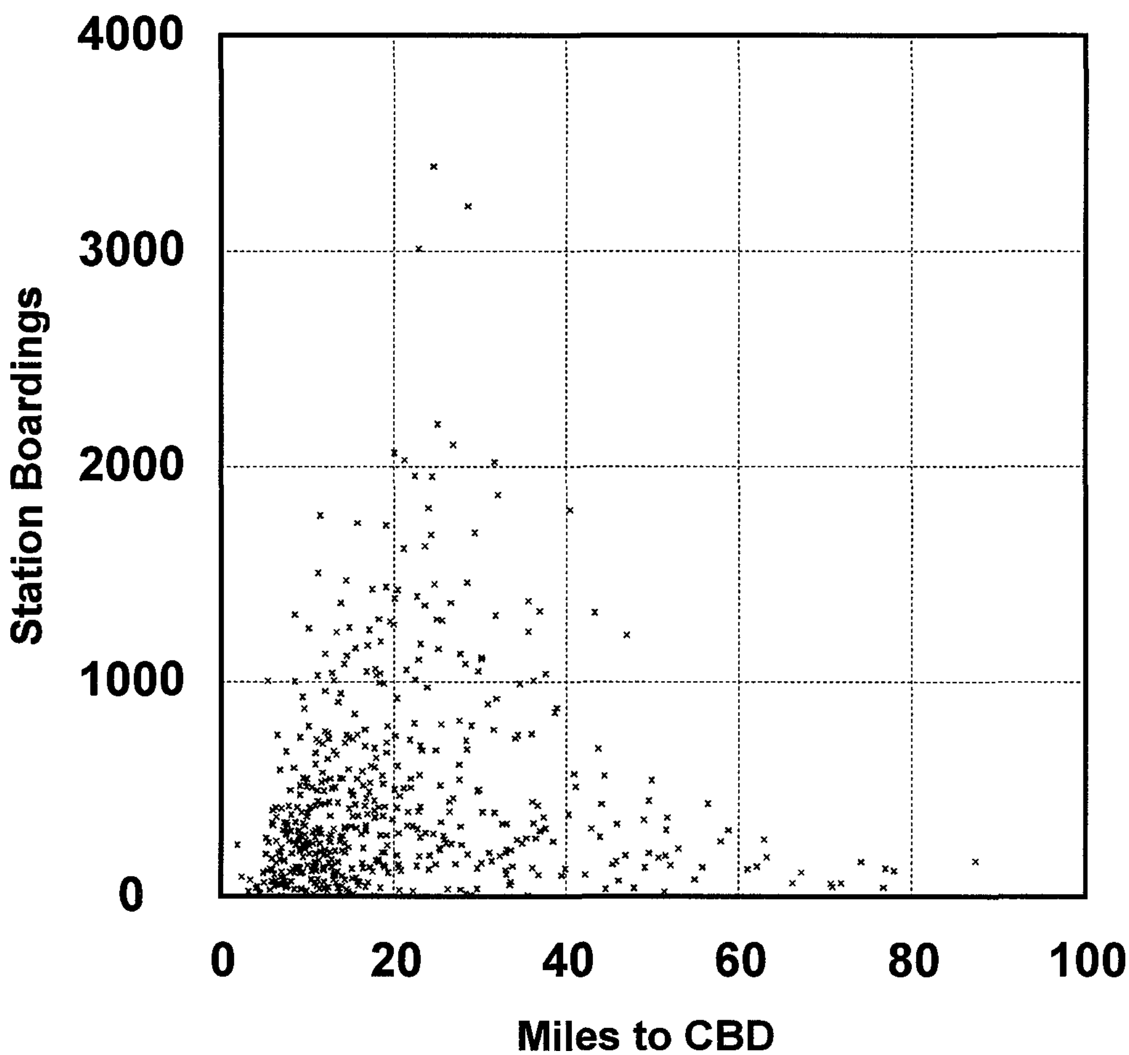

Table 6. Simple Correlation Coefficient Matrix Light Rail
(All variables converted to natural logarithms except dummy variables)

	Daily boardings	Miles to CBD	Minutes to CBD	Miles to nearest station	Terminal station
Daily boardings	1.000				
Miles to CBD	-0.225	1.000			
Minutes to CBD	-0.187	**0.859**	1.000		
Miles to nearest station	**0.400**	0.202	-0.048	1.000	
Terminal station (yes=1)	0.179	0.224	0.251	0.099	1.000
Number of daily inbound trains	**0.602**	-0.292	-0.122	0.083	-0.022
Number of parking spaces	0.226	0.365	0.156	**0.463**	0.236
Parking present (yes=1)	0.152	0.342	0.132	**0.435**	0.174
Feeder bus (yes=1)	**0.416**	0.058	-0.138	**0.446**	0.134
Population density (2 mile radius)	0.250	**-0.453**	-0.321	-0.338	-0.215
Population density (0.5 mile radius)	0.207	-0.328	-0.119	**-0.429**	-0.149
Average household income	-0.321	0.332	**0.509**	-0.373	0.088
Number of cars per household	-0.320	**0.649**	**0.564**	0.173	0.101
Number of CBD jobs	-0.168	-0.057	0.219	**-0.535**	-0.068
CBD size in acres	-0.196	0.167	-0.195	0.353	0.053
CBD jobs per acre	0.011	-0.126	0.236	**-0.510**	-0.069

	Number of daily in-bound trains	Number of parking spaces	Parking present	Feeder bus service	Population density (2 mile radius)
Number of daily inbound trains	1.000				
Number of parking spaces	-0.084	1.000			
Parking present (yes=1)	-0.115	**0.969**	1.000		
Feeder bus (yes=1)	0.019	0.240	0.199	1.000	
Population density (2 mile radius)	0.350	-0.382	-0.374	-0.068	1.000
Population density (0.5 mile radius)	0.379	-0.340	-0.342	-0.205	**0.758**
Average household income	-0.132	0.026	0.042	**-0.426**	-0.324
Number of cars per household	**-0.567**	0.396	0.389	0.001	**-0.724**
Number of CBD jobs	0.265	-0.365	-0.325	**-0.419**	**0.438**
CBD size in acres	**-0.456**	0.325	0.338	0.167	-0.319
CBD jobs per acre	**0.407**	-0.393	-0.377	-0.336	**0.432**

	Population density (0.5 mile radius)	Average household income	Number of cars per household	Number of CBD jobs	CBD size in acres
Population density (0.5 mile radius)	1.000				
Average household income	-0.031	1.000			
Number of cars per household	**-0.510**	**0.550**	1.000		
Number of CBD jobs	**0.506**	0.380	-0.296	1.000	
CBD size in acres	**-0.424**	-0.190	0.245	**-0.547**	1.000
CBD jobs per acre	**0.530**	0.332	-0.308	**0.885**	**-0.874**

Correlations greater than 0.400 shown in **Bold**.

Table 7. Simple Correlation Coefficient Matrix Commuter Rail
(All variables converted to natural logarithms except dummy variables)

	Daily boardings	Miles to CBD	Minutes to CBD	Miles to nearest station	Terminal station
Daily boardings	1.000				
Miles to CBD	0.152	1.000			
Minutes to CBD	0.011	**0.932**	1.000		
Miles to nearest station	**0.086**	**0.558**	**0.460**	1.000	
Terminal station (yes=1)	0.039	0.293	0.347	0.251	1.000
Number of daily inbound trains	**0.371**	-0.383	**-0.409**	**-0.468**	-0.141
Number of parking spaces	**0.642**	0.330	0.195	0.275	0.093
Parking present (yes=1)	0.380	0.196	0.152	0.121	0.054
Feeder bus (yes=1)	**0.120**	-0.191	-0.231	**-0.034**	-0.018
Population density (2 mile radius)	-0.024	**-0.507**	**-0.526**	-0.358	-0.084
Population density (0.5 mile radius)	0.010	**-0.474**	**-0.477**	**-0.353**	-0.049
Average household income	0.228	0.069	**0.022**	-0.008	-0.161
Number of cars per household	0.195	**0.514**	**0.434**	0.283	-0.020
Number of CBD jobs	0.255	0.120	0.027	**-0.119**	-0.070
CBD size in acres	-0.198	0.152	0.149	0.167	0.007
CBD jobs per acre	0.284	0.017	-0.050	**-0.168**	-0.055

	Number of daily in-bound trains	Number of parking spaces	Parking present	Feeder bus service	Population density (2 mile radius)
Number of daily inbound trains	1.000				
Number of parking spaces	0.089	1.000			
Parking present (yes=1)	0.080	**0.809**	1.000		
Feeder bus (yes=1)	0.142	0.039	-0.073	1.000	
Population density (2 mile radius)	0.236	-0.174	-0.163	0.372	1.000
Population density (0.5 mile radius)	0.239	-0.186	-0.191	0.378	**0.896**
Average household income	0.081	-0.189	0.151	-0.161	**-0.506**
Number of cars per household	-0.197	0.225	0.116	-0.070	**-0.595**
Number of CBD jobs	0.017	0.159	0.050	-0.061	-0.019
CBD size in acres	-0.114	0.055	0.040	0.205	0.075
CBD jobs per acre	0.067	0.092	0.018	-0.143	-0.050

	Population density (0.5 mile radius)	Average household income	Number of cars per household	Number of CBD jobs	CBD size in acres
Population density (0.5 mile radius)	1.000				
Average household income	**-0.465**	1.000			
Number of cars per household	**-0.546**	**0.649**	1.000		
Number of CBD jobs	-0.023	0.006	0.052	1.000	
CBD size in acres	0.025	-0.114	0.070	-0.318	1.000
CBD jobs per acre	-0.029	0.059	0.005	**0.893**	**-0.710**

Correlations greater than 0.400 shown in **Bold**.

Service variables: the chicken or the egg. Because the value of a variable that indicates the amount of service offered is usually in response to demand, the use of such variables is not helpful in explaining why the demand is there in the first place. However, the use of variables that describe the presence of such service, rather than the amount, can be useful in explaining a potential transit riders motivation in choosing transit. Thus, the variables indicating the amount of parking, feeder bus service, and service frequency were dropped, despite their high correlations with passenger boardings, and the variables that indicated the presence of feeder bus or parking were retained.

Distance to the CBD. Figure 2 shows the strong relationship between distance to the CBD and station boardings for the commuter rail stations; ridership rises with distance and then falls off precipitously. Accordingly, the fitting of distance to the CBD for commuter rail tested non-linear curves on the log-log scale. Light rail ridership too is a function of distance, but ridership declines more consistently with distance to the CBD.

Employment density and employment size. Each of these variables has a logic for its use, but they are highly correlated with each other, making their use as separate variables suspect. To solve this dilemma, various transformations of a variable that combines these into one variable were tried as part of the analysis. For the light rail equation the best fitting employment term combined the two in the form of employment multiplied by the natural logarithm of employment density. When that variable was tried for the commuter rail equation the coefficient for employment was so small as to show little impact of employment size. Employment density alone was the strongest employment variable for commuter rail.

Population density. The population found within both two-mile bands and half-mile bands, as best as can be defined by census tracts, was constructed for each station. The two-mile band width has the superior fit for both modes.

Terminal station. Stations at the end of each line farthest from the CBD were tested to see if they attract added riders, since they can draw from a wider commutershed beyond the end of the line. This variable proved significant for the light rail equation, but not for commuter rail, perhaps because commuter rail lines generally extend farther into the country-side.

Clearly there are innumerable possible combinations of predictor variables that can be tried and many were, with varying degrees of success. To narrow these down, variables were eliminated if a similar one captured the same explanatory effect, but performed less well than others. For example, this resulted in choosing **distance to the CBD** over the travel time to the CBD.

3.3 RESULTS

Multiple linear regression is used here, with the natural logarithm of total daily boardings at stations outside the CBD as the dependent variable. If the natural logarithms of the independent variables are also used, the resulting model is multiplicative in nature once the transformation is undone.[4]

[4] This type of model minimizes the squares of the *percent* differences between the observed and the predicted value. Therefore, an actual ridership of 100 which is predicted to be 120 has a larger

In Table 8 the variables that were included in the final model are shown in bold, and some of the key variables rejected are also shown. The details for the two best fitting models are shown in Table 9 and Table 10.

While the R-squared for these two equations are not especially high, particularly for the commuter rail equation, each of the variables in both the light rail and commuter rail equations are significant at the 0.01 level. This means that a change in the level of one of the independent variables almost certainly is associated with a change in the dependent variable.

The weaknesses in the explanatory power of the variables can be attributed to many factors. Some may fall in the category of model specification, wherein the variables chosen (or not chosen) do not fully describe the phenomenon in question. Regarding specification, the models assume that the propensity to travel to the CBD in each area along a corridor is a function of only the distance to the CBD and the CBD's pulling power. But some areas may have relatively stronger pulls to other destinations, either because of the proximity of large attractions or of some special community of interest or affinity. The models do not account for the relative attractiveness of the automobile alternative. The models also do not account for the attractiveness that a transit line may have if it is well connected to other transit lines in the network that could provide service outside the CBD, or about the specific kinds of bus connections available at stations.

Others weaknesses may be because of weak data. The imprecision associated with the definition of the CBD, for example, has an effect. The arbitrariness of the ZIP code areas in relation to the concentration of non-residential activities undoubtedly has created a problem. Also, the employment densities in the CBD may be distorted by the necessary inclusion of large areas without much employment, which understates the density of the relevant portions of the CBD. This would appear to have its greatest impact in smaller CBDs such as Sacramento and San Diego. Similarly, the large size of census tracts, particularly in lower density areas, may distort the population densities estimated within two miles of stations.

The boarding counts include riders that may have disembarked prior to the CBD. Although those numbers were small relative to the CBD in general, there may have been cases where these volumes were significant. They might also include riders who were traveling away from the CBD rather than toward it.

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residual i.e., has a poorer fit than a situation where the actual ridership is 1,000, which is predicted to be 1,100.

Table 8. Summary Results of Modeling Station Boardings

Variable	Light Rail	Commuter Rail
Employment	CBD jobs CBD job density **CBD jobs & job density**	CBD jobs **CBD job density** CBD jobs & job density
Population	**density within 2 miles** density within 1/2 mile	**density within 2 miles** density within 1/2 mile
Access	**some feeder bus** **parking available**	**some feeder bus** **parking available**
Distance to CBD	**log linear**[5] quadratic	log linear **quadratic**[6]
Competition	**nearest station** nearby line	nearest station nearby line
Income	income	**income**
Terminal?	**yes**	yes
CBD Terminal Distance	not applicable	no

The table lists all factors that were considered in the analysis. **BOLD** type indicates the variables that are statistically significant in the best-fitting models.

[5] For light rail, boardings decrease with distance from the CBD following a downward sloping curve or log-linear function.

[6] For commuter rail, boardings increase with distance from the CBD up to about 35 miles from the CBD and then decline with increasing distance as modeling by a quadratic function.

Table 9. Model of Light Rail Station Boardings

Dependent Variable: Log of Daily Boardings N: 261 Multiple R: 0.732
Squared Multiple R: 0.536 Adjusted Squared Multiple R: 0.523 Standard Error Of Estimate: 0.962

VARIABLE	COEFFICIENT	STD ERROR	STD COEF	TOLERANCE	T
Constant	5.390	0.431	0.000		12.518
Terminal Station	1.031	0.235	0.197	0.906	4.385
Parking present	0.419	0.151	0.140	0.714	2.772
Feeder bus	0.842	0.140	0.303	0.728	6.031
Log of miles to nearest station	0.892	0.098	0.507	0.586	9.061
Log of miles to CBD	-0.597	0.124	-0.238	0.747	-4.800
Log of population density	0.592	0.129	0.255	0.595	4.595
Number of jobs × employment density	0.00110	0.00017	0.359	0.572	6.331

Table 10. Model of Commuter Rail Station Boardings

Dependent Variable: Log of Daily Boardings N: 526 Multiple R: 0.585
Squared Multiple R: 0.343 Adjusted Squared Multiple R: 0.334 Standard Error Of Estimate: 0.927

VARIABLE	COEFFICIENT	STD ERROR	STD COEF	TOLERANCE	T
Constant	-11.288	1.785	0.000		-6.322
Parking Present	1.173	0.142	0.311	0.893	8.256
Feeder bus	0.449	0.090	0.183	0.848	4.710
Log of miles to CBD	0.852	0.160	0.477	0.157	5.309
Miles to CBD × Log of Miles to CBD	-0.0054	0.00161	-0.293	0.166	-3.352
Log of population density	0.249	0.060	0.216	0.471	4.170
Log of household income	0.877	0.154	0.254	0.641	5.699
Log of employment density	0.715	0.101	0.264	0.917	7.093

The two equations can be written as:

LR: Log of Daily Boardings = 5.390 + 1.031 × Terminal Station + 0.419 × Parking Present + 0.842 × Feeder Bus + 0.892 × Log of Miles to Nearest Station - 0.597 × Log Miles to CBD + 0.592 × Log of Population Density + 0.00110 × (Employment Density × Log of Number of CBD Jobs)

CR: Log of Daily Boardings = -11.288 + 1.173 × Parking Present + 0.449 × Feeder Bus + 0.852 × Log Miles to CBD - 0.0054 × (Miles to CBD × Log of Miles to CBD) + 0.249 × Log of Population Density + 0.877 × Log of Average Household Income + 0.715 × Log of CBD Employees Per Acre

When the transformation on these two equations are undone, the multiplicative nature of the equation becomes clear. For the dummy variables of Terminal Station (light rail only), Feeder Bus, and Parking Present a yes means that the coefficients of each of the variables become constant multipliers. For the continuous variables the coefficients become exponents for each variable. Because the regression is based on minimizing the percent differences in predicted and actual station boardings, there is a built in bias against stations with higher ridership. An adjustment of a constant multiplier is required to these equations shown below in brackets at the beginning of each equation.[1]

Light Rail total daily boardings =
[1.588][219.2 × 2.82 [If terminal] ×
1.52 [If parking present] × 2.32 [If feeder bus] ×
Miles to nearest station^ (0.892) ×
Miles to the CBD ^ (-0.597) ×
Residential density ^ (0.592) ×
1000's of employees ^ (0.00110 × Employment Density)]

Commuter Rail total daily boardings =
[1.537][0.0000125 × 3.18 [If parking present] ×
1.53 [If feeder bus] ×
Average Household income ^ (0.877) ×
Residential density ^ (0.249) ×
Miles to the CBD ^ (0.852 - 0.0054 × Miles to CBD)
× Employment Density ^ (0.715)]

These equations allow for the computation of predicted ridership values, and therefore the residual values, i.e. the observed minus the expected. (Recall however, that the algorithm used minimizes <u>percent</u> differences, not absolute differences.) The residuals in theory should be randomly dispersed, with no detectable patterns. The truth is that patterns exist, which can perhaps lead us to see ways to improve the model. For example, some cities display consistently positive residuals while the stations of other cities are usually overpredicted. This might indicate that a city has odd topographic features, extremely congested highways, expensive fares, intermediate attractions, or any other of a multitude of possible factors that were not corrected for in this analysis. To explore this, actual

[1] The correction is given by the formula:
predicted value = e^(predicted value on log scale) * e^(variance on log scale/2)

boardings for each line used to calibrate the model were summed and compared to the sum of the boardings predicted for each line.

In Figure 3 and Figure 4 the accumulated daily ridership on each rail line in the data set was calculated using the two multiple regression equations and compared to the actual ridership on the lines. An observation in these scatterplots that falls near the 45 degree line indicates that the line's ridership is estimated well. A point below the line indicates the line is overpredicted and a point above the line indicates an underprediction. For the light rail equation the more lightly used lines tend to be overpredicted. The commuter rail plot in Figure 4 shows less of that type of bias.

The sensitivity of passenger boardings as a function of each of the variables is shown in Table 11 by indicating the impact of a 100 percent increase in each independent variable. For the dummy variables — the presence of parking, feeder buses and a terminal station — Table 11 indicates the impact of a positive answer.

This side by side comparison of each variable's impact demonstrates the key differences in the two equations. For light rail stations the presence of feeder bus service is especially important, with parking availability of less relevance. Conversely, commuter rail stations depend to a much greater degree on parking availability and less so on the presence of feeder buses.

Figure 3.
Predicted Versus Actual Ridership
by Light Rail Line

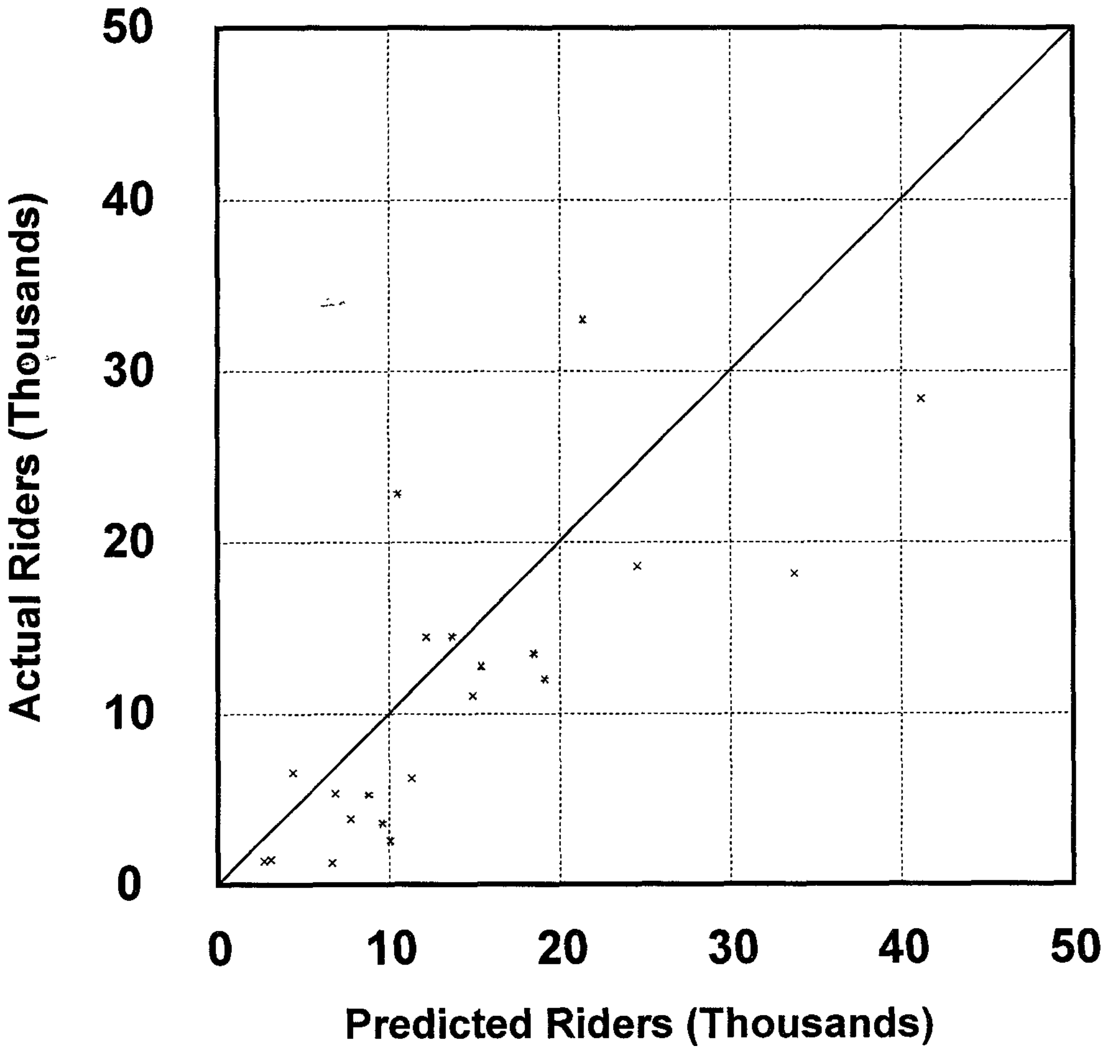


Figure 4.
Predicted Versus Actual Ridership by Commuter Rail Line

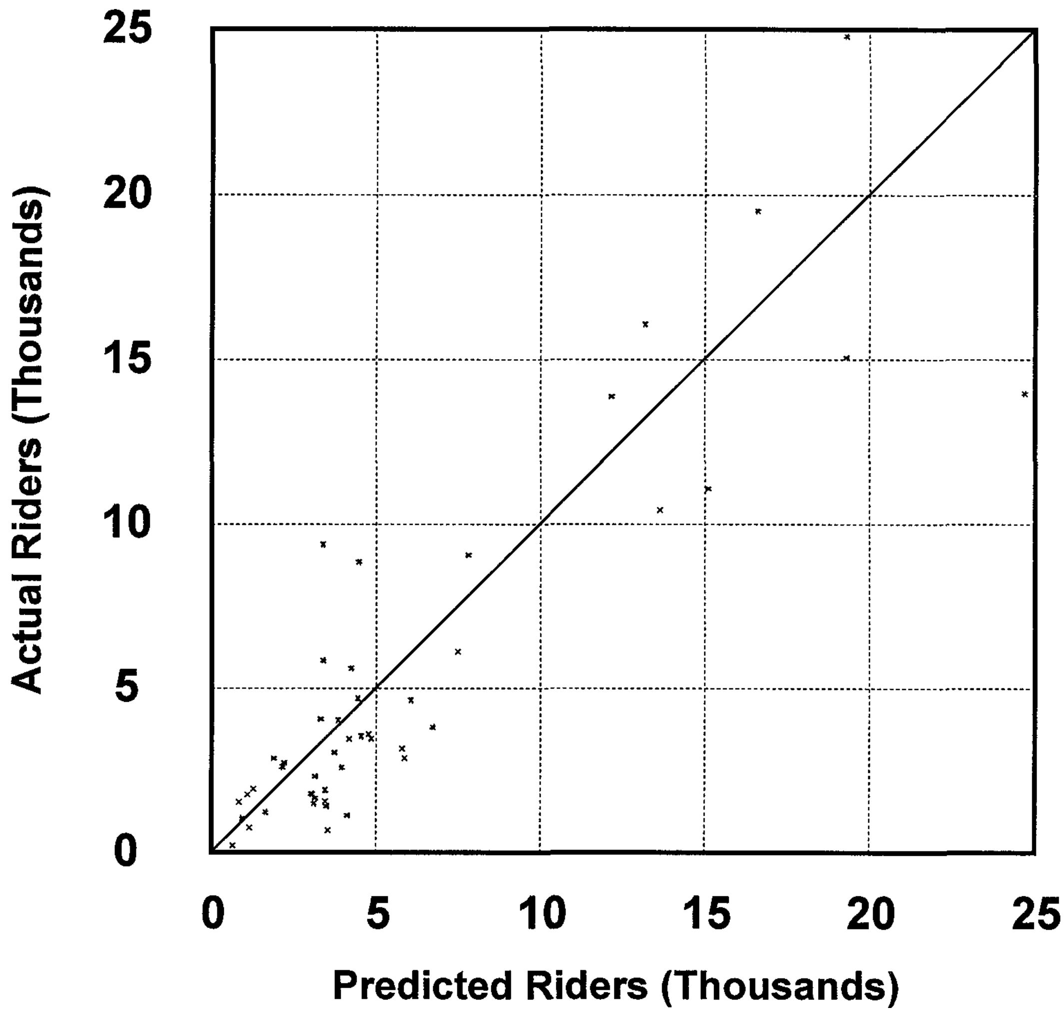


Table 11. Station Boarding Sensitivities

Percent Change in Ridership Resulting from 100 Percent Change in Each Variable*

Independent Variable	Light Rail	Commuter Rail
Terminal*	178	na
Parking*	52	218
Feeder bus*	132	53
Population density	50.7	18.8
Income	na	83.7
CBD employment **	7.7	na
CBD employment density ***	33.8	64.1
Distance to CBD	-33.9	na
(from 15 to 30 miles)	na	29.0
(from 40 to 80 miles)	na	-40.6
Distance to nearest station	85.6	na

* *Table shows the impact of a "yes" answer for these dummy variables.*

** *For light rail, varies with CBD employment density; percent change shown for employment density of 100 jobs per acre*

*** *For light rail, varies by CBD employment; percent change shown for employment of 200,000 jobs*

The impact of population densities is almost three times as great for light rail stations as it is for commuter rail, but the income of the potential riders living near commuter stations is of greater impact, with higher incomes producing more riders. Income was not a factor for light rail. Employment in the CBD is a factor for both modes but in different ways. For light rail higher employment and employment densities each had a positive impact on ridership. For commuter rail employment densities had a significant impact but total employment in the CBD did not. Caution should be taken with this particular finding since employment and employment density are highly correlated. Moreover, the observation set, with the commuter rail stations located in regions with much higher CBD employment, may have affected the results of these variables.

Another difference between the two modes is the behavior of ridership with respect to distance. For light rail, the expected drop-off of ridership occurs — each doubling of distance reduces ridership at a station by one-third. Commuter rail behaves quite differently, with ridership growing with distance — up to about 35 miles when ridership begins to fall off. This perhaps can be explained by the smaller payoff at close distances in choosing the high speed rail mode, with distances in the 20 to 35 mile range giving large time benefits. Beyond 35 miles the time benefits are offset by the sparser population. Finally, the spacing of stations can impact ridership; when stations on a line are close, as with light rail, they can compete with one another, shrinking the numbers boarding at a particular station. For commuter rail the average two-mile station spacing does not present that problem.

To illustrate these equations, a series of graphs in Figures 5 to 12 show the predicted boardings at stations for various values of the variables. In each graph a family of lines is shown with distance to the CBD on the x-axis and predicted boardings on the y-axis. For each exhibit all variables but one are held constant to show how much change is produced by the variations. Figures 5 through 8 show these relationships for light rail stations and Figures 9 through 12 show them for commuter rail.

In each of the figures all the variables are held constant except distance to the CBD and the variable of interest. For light rail, the constants assume stations on a line with the following characteristics:

- low density suburban area
- widely spaced stations
- about average CBD size and density
- feeder bus service is available.

For commuter rail, the constants assume stations on a line with the following characteristics:

- average density CBD
- higher income suburban area
- park-and-ride lots are available at stations

For all the light rail curves in Figure 5 through 8 station ridership falls with distance to the CBD. In Figure 5, light rail boardings are shown as a function of distance to the CBD for four levels of CBD employment ranging from 25,000 to 200,000 jobs. The level of employment does not have a large effect on ridership, except at stations under five miles from the CBD where the steepness of curves hides the difference in ridership by employment levels. While the differences between the highest and lowest employment levels at 20 miles appears to be about 200 riders, at about three miles from the CBD the highest employment level produces about 700 more trips that the lowest one. Figure 6 compares ridership for varying CBD employment densities. Here the variation is more pronounced with higher employment densities accounting for a large increase in ridership. Again, the impact is more exaggerated close in to the core.

In Figure 7 the residential density is varied to show how it affects ridership at light rail stations. It has a pronounced effect; densities of 10 people per acre produce about three times the number of riders as densities of two per acre. The impact of access services available at stations are shown in Figure 8. For light rail stations the addition of feeder buses has a more pronounced effect on ridership than does the availability of parking, and of course, supplying both feeder buses and parking has the greatest effect.

Figures 9 through 12 show the variation of commuter rail station ridership with distance to the CBD for a series of variables. In all cases the concave shape of the curves reflects the rising ridership with distance until about 35 miles, after which it begins to fall. In Figure 9, CBD employment levels ranging from 50,000 to 300,000 jobs are depicted, showing large increases in ridership with higher CBD employment levels. Note that the effect is greater for commuter rail than was seen for light rail in Figure 5 and Figure 6 where variations in employment numbers and density were shown.

Residential densities are varied in Figure 10 to depict the effect of rising density on ridership. Here the impact, while substantial, is somewhat less than what was seen in Figure 7 for light rail. Tied closely to residential densities is the income variable, shown in Figure 11. Rising income means more commuter rail riders, reflecting the high cost of using that mode. This effect tends to offset the effect of lower densities on depressing ridership, since lower densities and higher incomes are strongly associated with one another.

Finally, Figure 12 depicts the impact of access modes available at commuter rail stations. For commuter rail the impact of access modes is much stronger than it was for the light rail equation, and the order of impact is reversed between feeder buses and parking. For commuter rail, parking availability boosts ridership much more than feeder buses do; for light rail the reverse is true.

Figure 5.
Light Rail Station Boardings
by Distance to the CBD
and CBD Employment Levels

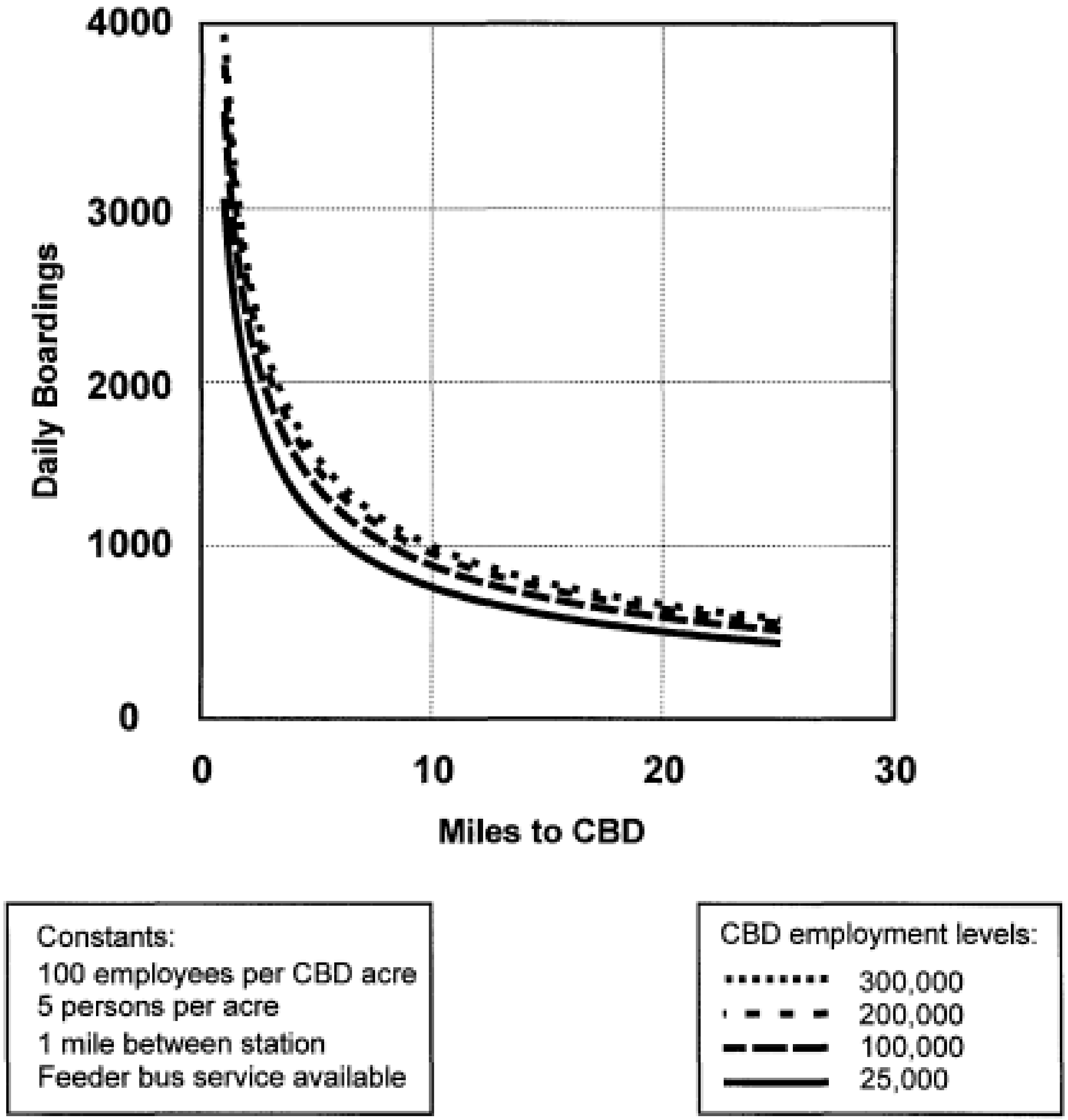


Figure 6.
Light Rail Station Boardings
by Distance to the CBD
and CBD Employment Density

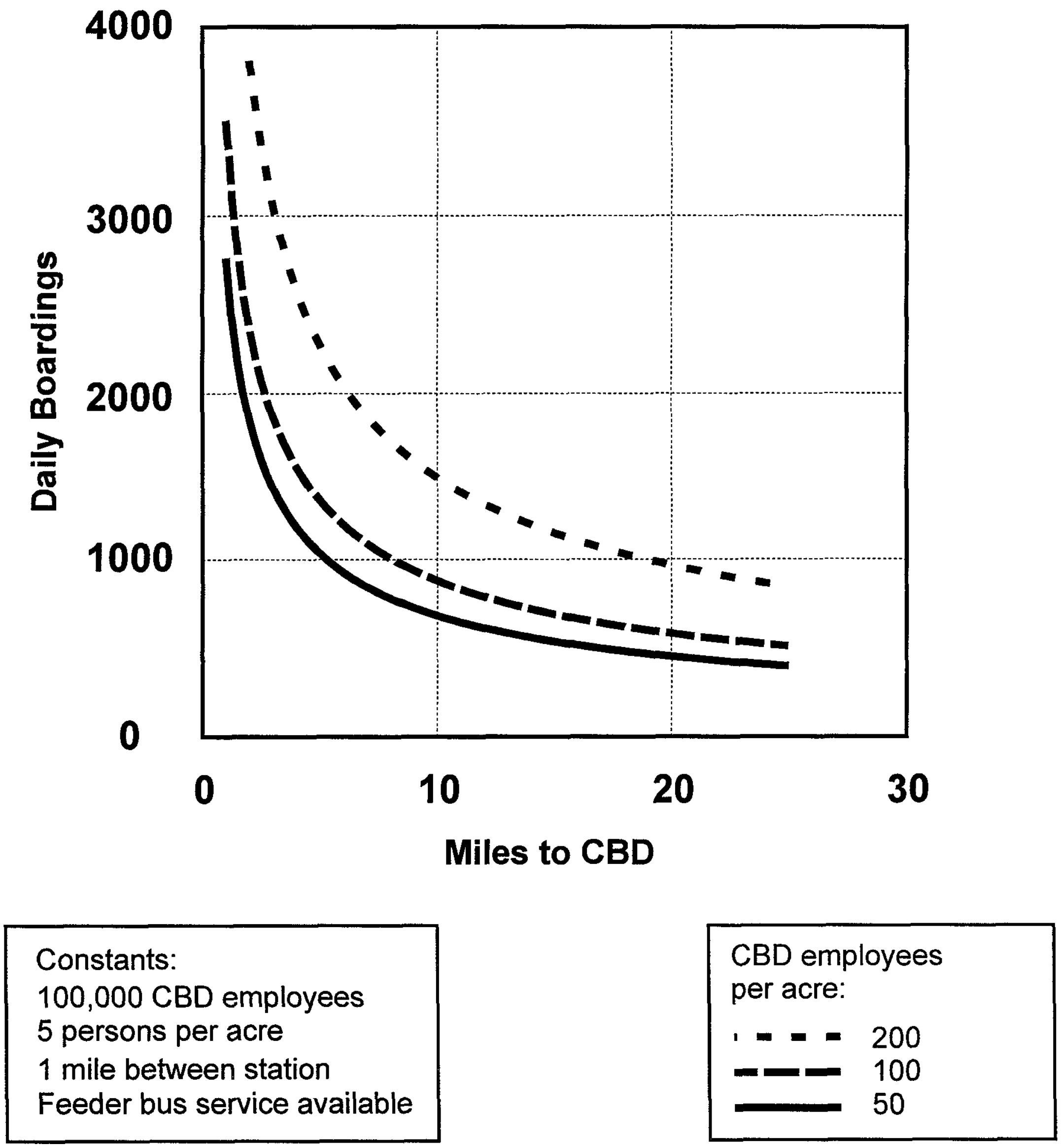


Figure 7.
Light Rail Station Boardings
by Distance to the CBD
and Residential Density

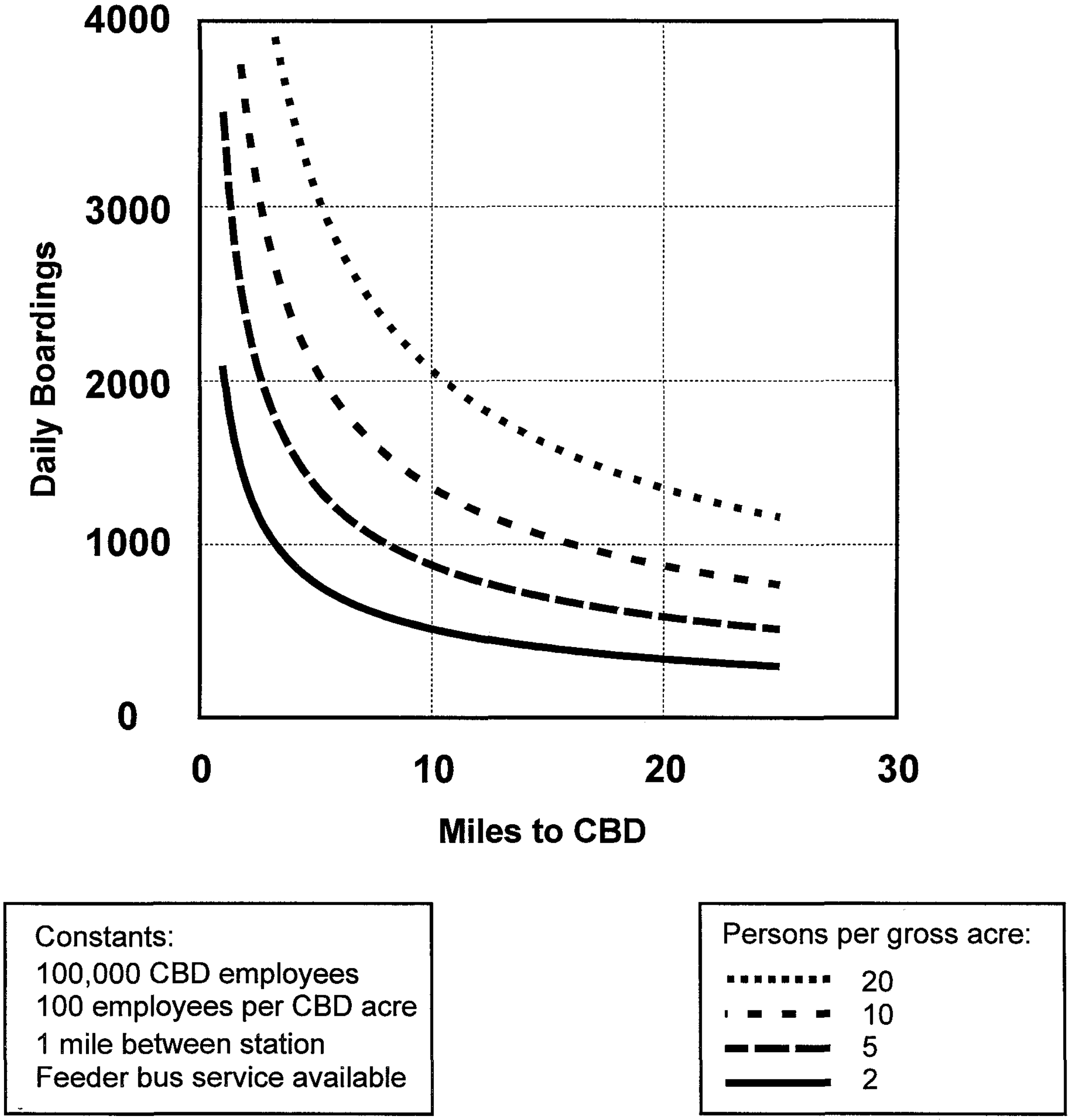


Figure 8.
Light Rail Station Boardings
by Distance to the CBD
and Access Modes

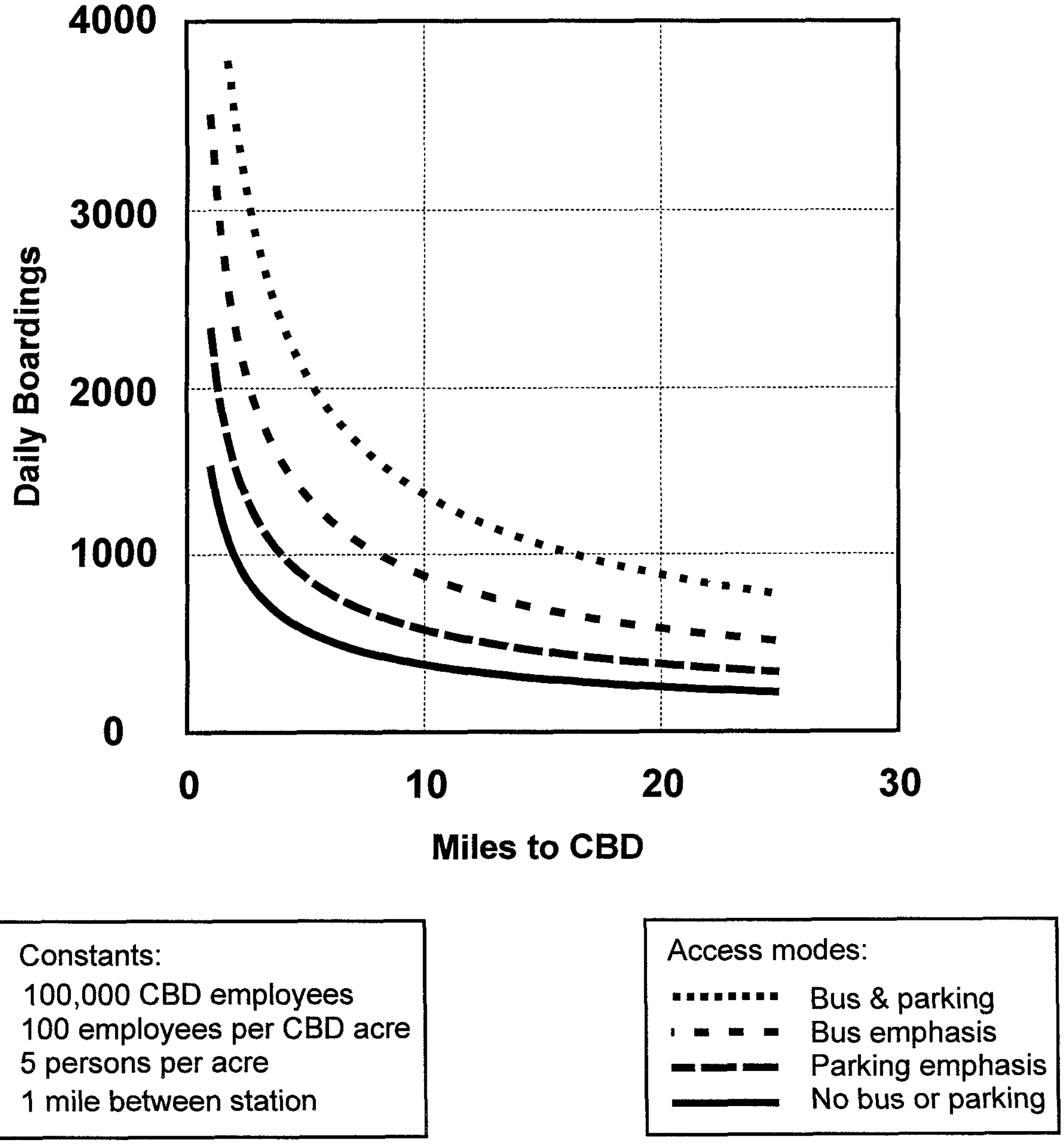


**Figure 9.
Commuter Rail Station Boardings
by Distance to the CBD and
CBD Employment Density**

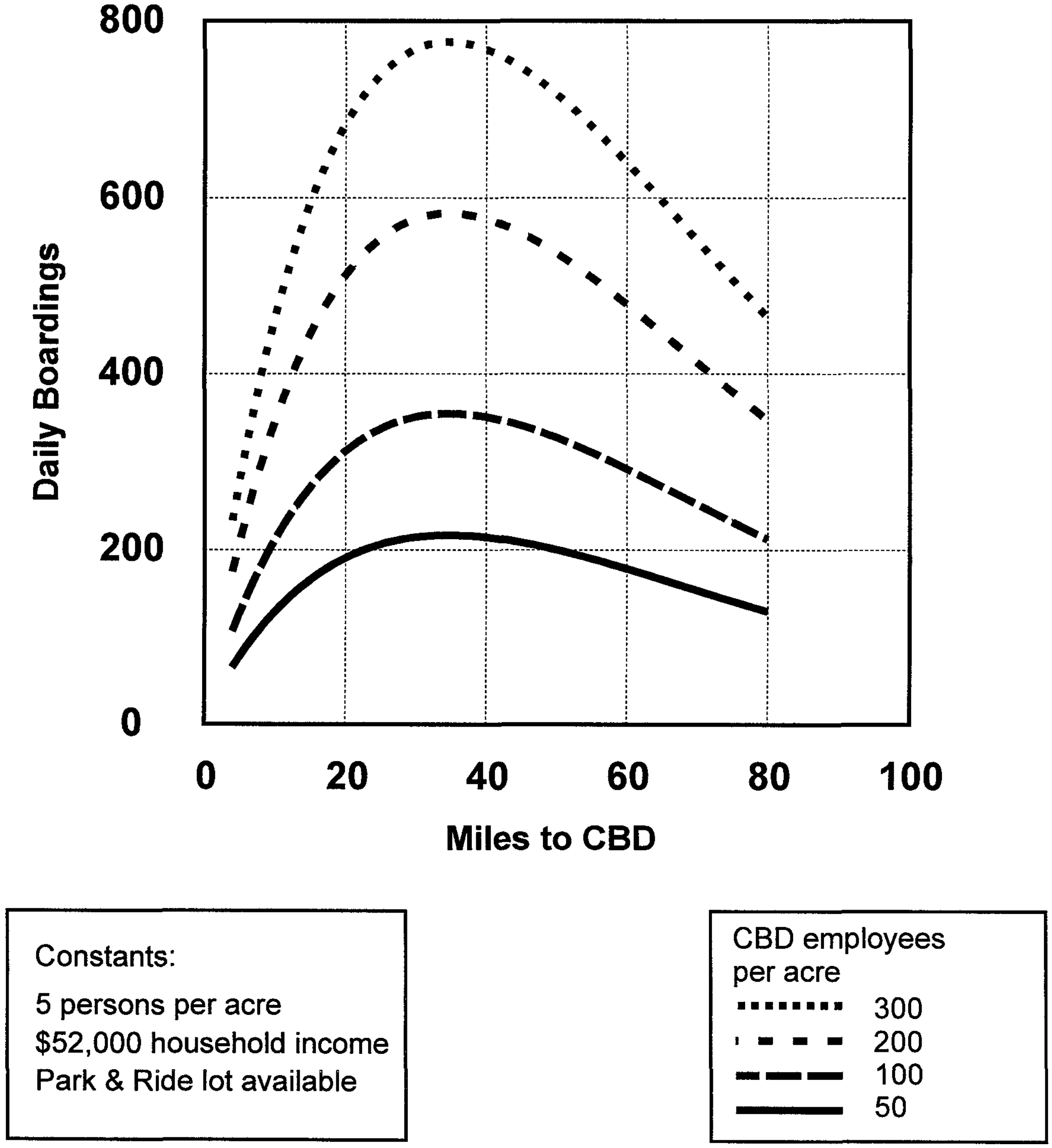
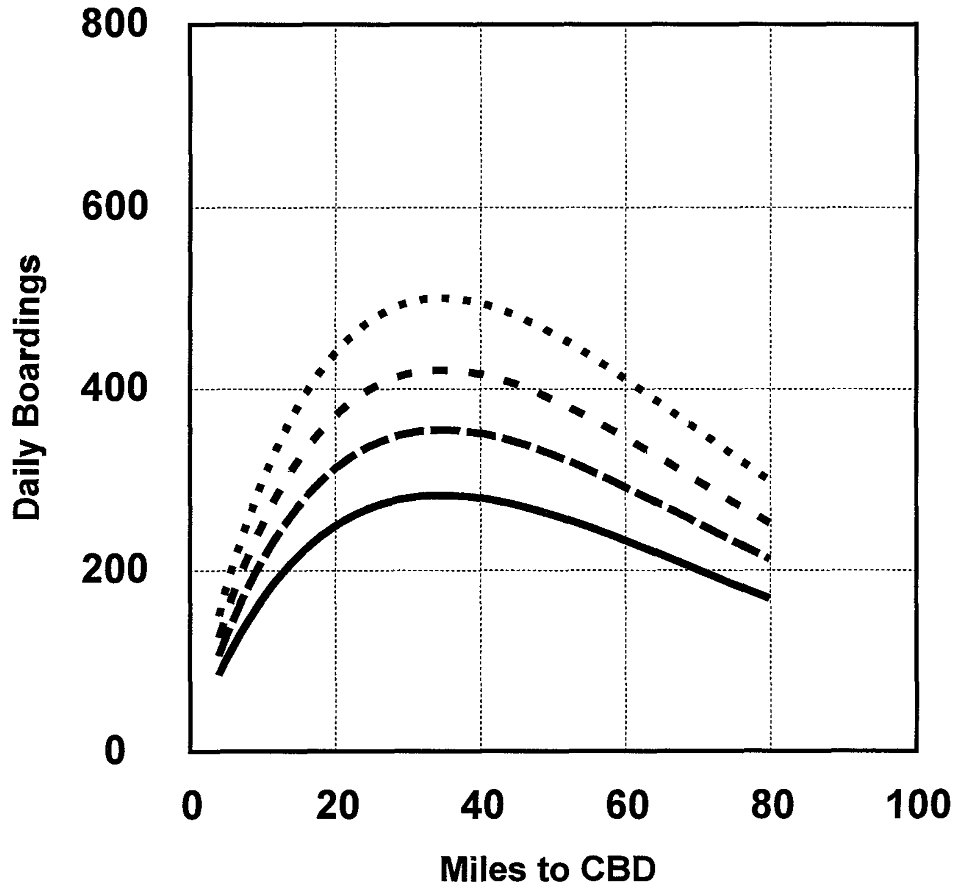


**Figure 10.
Commuter Rail Station Boardings
by Distance to the CBD
and Residential Density**



Constants:

100 employees per CBD acre
$52,000 household income
Park & Ride lot available

Persons per gross acre

- 20 (dotted)
- 10 (short dash)
- 5 (long dash)
- 2 (solid)

**Figure 11.
Commuter Rail Station Boardings
by Distance to the CBD
and Household Income**

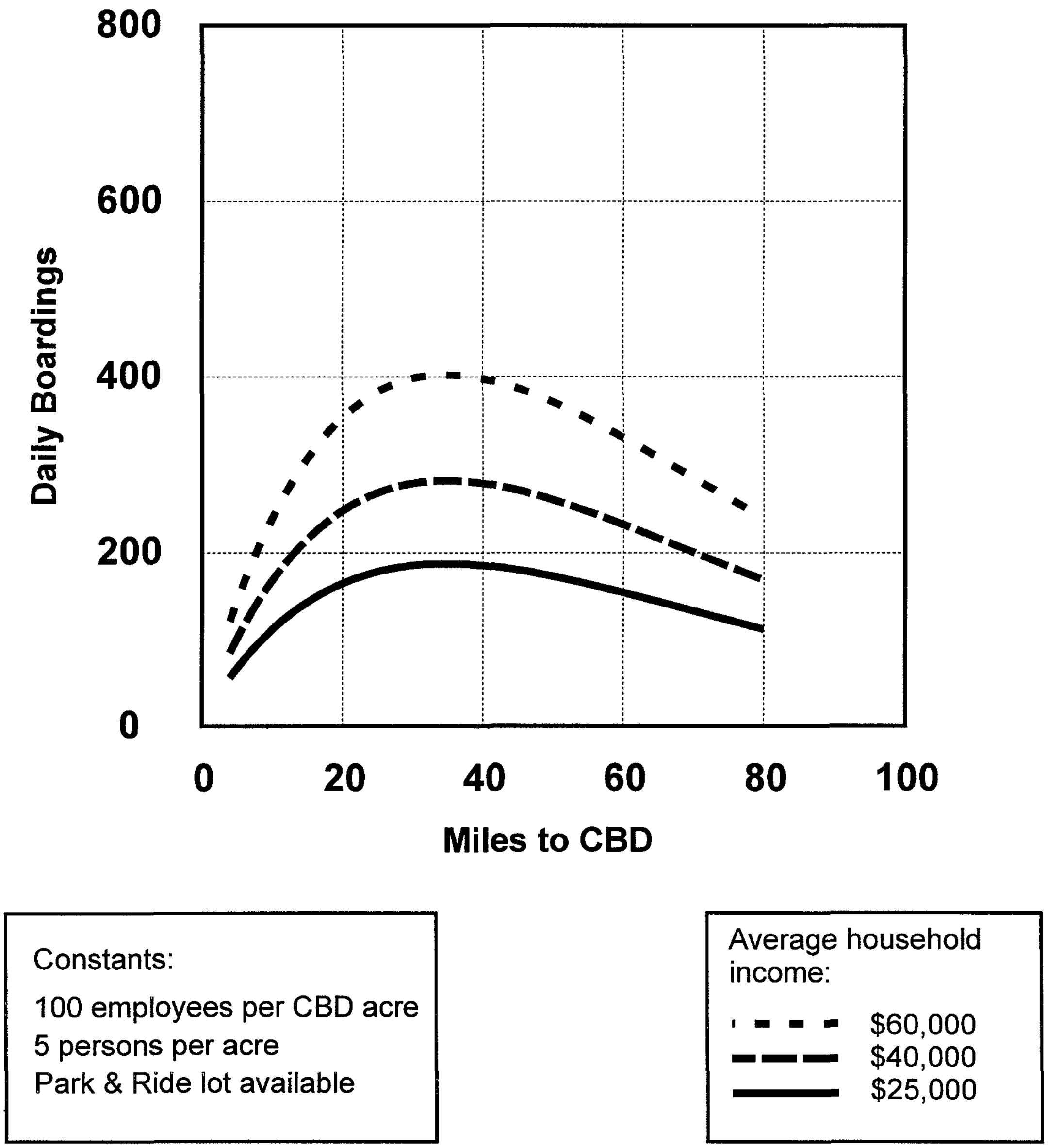
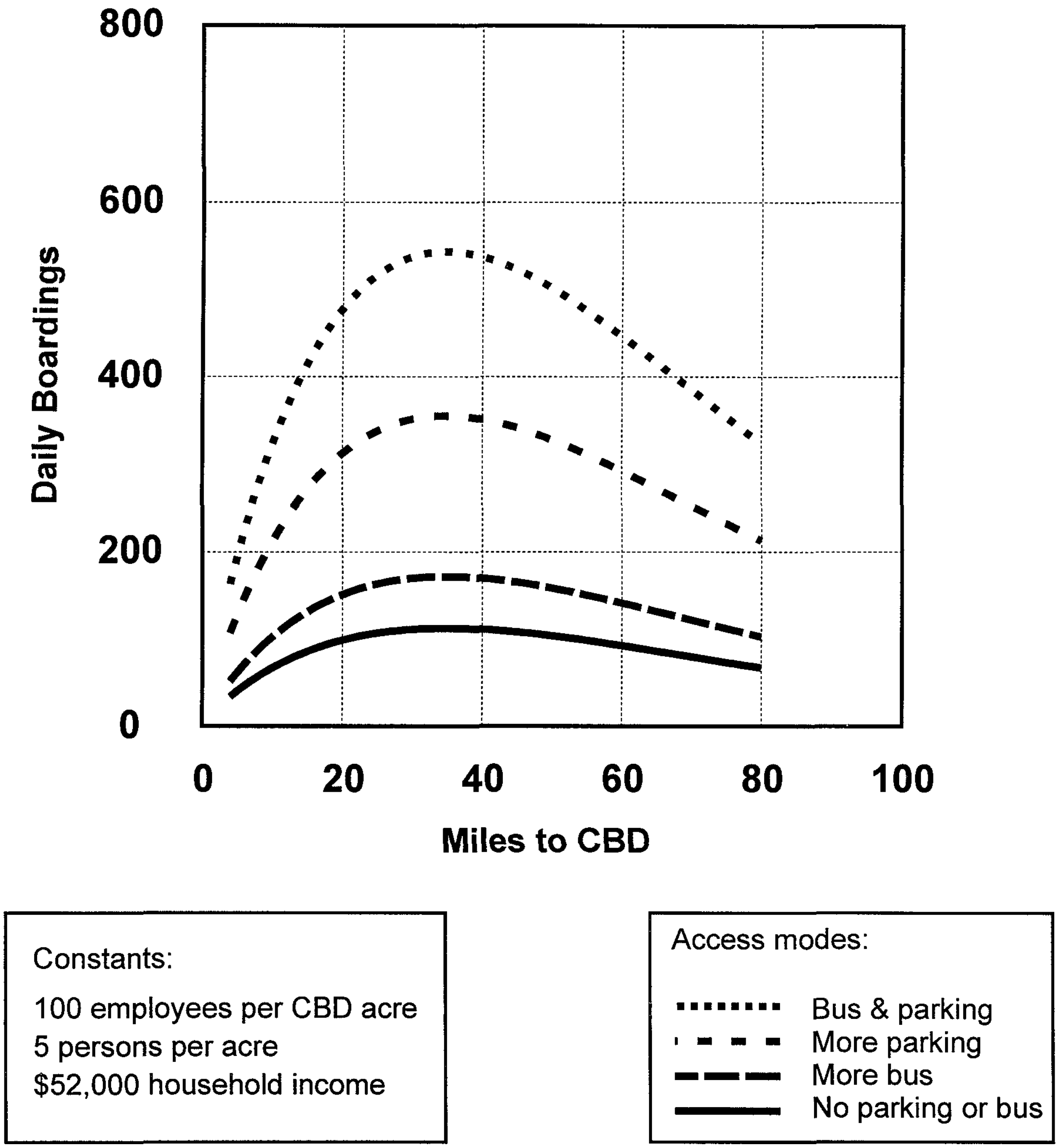


**Figure 12.
Commuter Rail Station Boardings
by Distance to the CBD
and Access Modes**



4.0 HYPOTHETICAL CORRIDOR DEMANDS

4.1 HYPOTHETICAL CORRIDORS

To establish the travel demand for a corridor transit line the daily boardings for each station in a corridor were estimated using the two models in the previous section of this report. A series of hypothetical light rail lines were established to reflect the full range of possible values of the relevant variables that might be reasonable encountered. One directional line ridership was assumed to be the sum of daily boardings on all stations outside the Central Business District.

For light rail lines, the corridor demand was constructed by varying the values of the following variables:

- CBD employment size
- CBD employment density
- population density (within two miles of station) gradient as a function of station distance from the CBD
- line length (with assumption of station spacing determining the number of stations)
- distance to the nearest station (station spacing)
- proportion of stations with substantial parking
- proportion of stations with bus feeders

And for the hypothetical commuter rail lines:

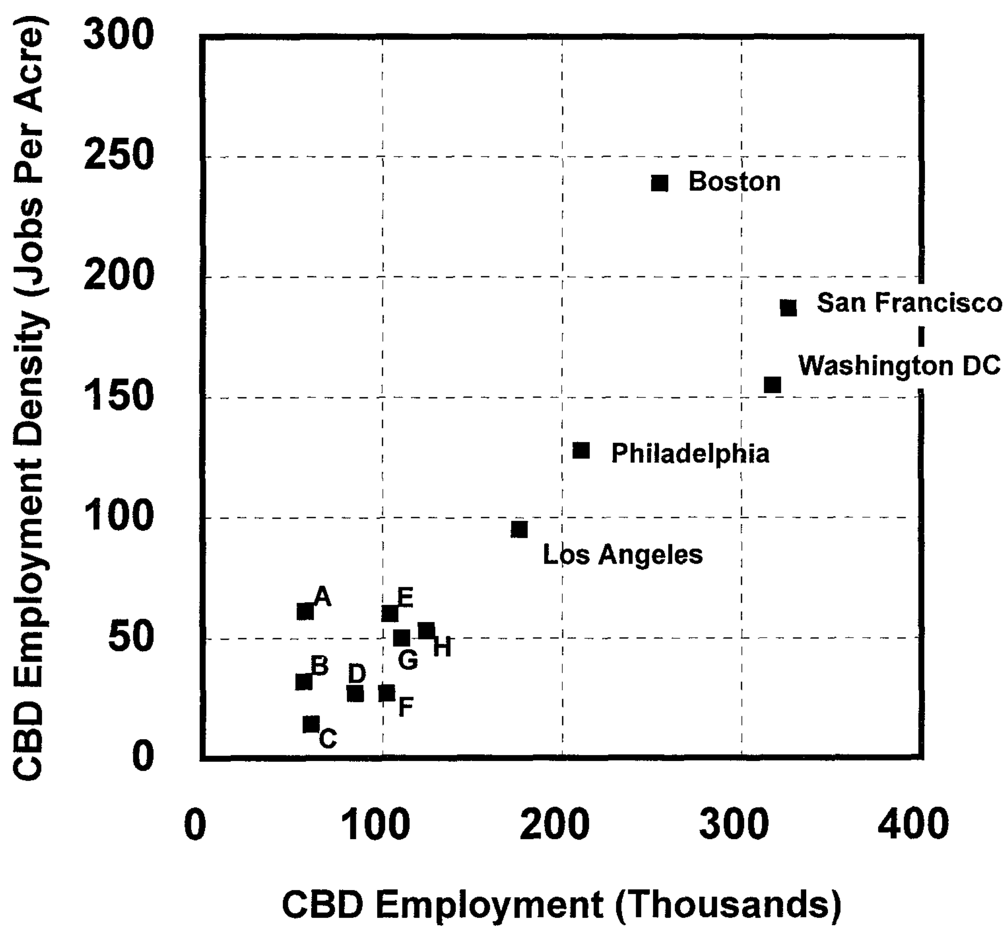
- CBD employment size
- population density (within two miles of station) gradient as a function of station distance from the CBD
- line length (with assumption of station spacing determining the number of stations)
- proportion of stations with substantial parking
- proportion of stations with bus feeders
- income in residential area near station

To frame the full but realistic range of possible values of variables, plots of various combinations were made. For example, the plot of the relationship between employment size and density shown in Figure 13 helped to circumscribe the values for possible combinations of these two variables. (See Appendix E for further details.)

For the hypothetical light rail lines, eight values of employment size were used ranging from 25,000 to 300,000 jobs. Employment densities were estimated for each of these CBD employment sizes by assuming a less dense three square mile CBD and a more dense two square mile one.

For the commuter rail lines, seven values of CBD employment size were used ranging from 75,000 to 400,000 jobs. Since employment size did not directly enter the commuter rail equation the employment sizes were converted to employment densities. Thus, each employment size was tested with a low and high employment density. These ranged from a low of 39.1 jobs per acre for the low density three square mile CBD of 75,000 jobs to a high of 312.5 jobs per acre for a high density two square mile CBD of 400,000 jobs.

Figure 13.
CBD Employment Numbers and Density:
13 U.S. Rail Cities



A	**Portland, OR**
B	**Buffalo, NY**
C	**Sacramento, CA**
D	**San Diego, CA**
E	**Baltimore, MD**
F	**Cleveland, OH**
G	**St. Louis, MO**
H	**Pittsburg, PA**

<u>Note:</u>
There are no standard definitions of CBD's. These measures are based on the definitions used in this analysis which utilizes zip code areas

Plots of population densities as a function of distance for each of the light rail and commuter rail cities were done to establish a range of likely density gradients. Four different population densities gradients are used for each type of service. For light rail the gradients were designated as high, medium, and very low. The high gradient has 23 people per acre at one mile from the CBD, dropping to nine per acre at 10 miles and four per acre at 20 miles. The medium gradient has 18, 5, and 3 per acre at those distances and the low has 15, 3, and 2 people per acre. The light rail residential density gradients are shown in Figure 14.

For the commuter rail gradients the high and medium gradients of the light rail line were used, but a very high gradient was added to account for the very high densities found near the CBDs of the largest cities. Also tested was a shallow density gradient to account for large cities, particularly in the west, where densities are low close to the CBD and drop relatively little at increasing distances from the CBD. The commuter rail residential density gradients are shown in Figure 15.

The units of population density used here are persons per gross acre, developed here for expediency. The reader should keep this in mind since other studies use other measures of population density. Other potential measures of density include persons, households, or dwelling units per developed acre and persons, households, or dwelling units per net residential acre. Measures per developed acre subtract the amount of land that is available for development (i.e. currently vacant or in agriculture or forestry) from the total acreage. The amount of land that is vacant or otherwise developable can vary widely. Analysis of land within one-half mile of BART stations in the San Francisco Bay Area and Metra and CTA stations in Chicago done for other research topics shows that anywhere from 0 to 50 percent of the land around stations may be undeveloped. Suburban and rural stations are most likely to have large amounts of undeveloped land.

Measures per net residential acre subtract the amount of land in parks, streets and other right-of-ways, and non-residential uses from the number of developed acres. A 1992 Planners Advisory Service Memo on land use ratios indicates that, on average 50 percent of the developed land in cities is residential. This ratio can vary from 25 to 75 percent, with smaller cities showing the greatest variability. Station areas can vary even more. BART station areas have a minimum of 20 percent of land within a half-mile in residential uses, but some downtown Chicago stations have no land devoted to residential uses. Station areas that are primarily residential, whether suburban or in the city of Chicago, have about 60 percent of station area land devoted to residential purposes.

To determine how best to depict the income variable in the commuter rail equation, plots of income versus distance and of income versus population density were examined. The latter shows that a closer relationship exists between income and population density. Accordingly, neighborhood incomes are assigned as a function of population density. Incomes range from $20,000 for the highest density neighborhoods to $60,000 for low density areas, as shown in Figure 16. For distances beyond 40 miles from the CBD income was capped at $43,000 to reflect the distance-income-density frequencies observed in the data set.

**Figure 14.
Assumed Residential Density Gradients:
Hypothetical Light Rail Corridors**

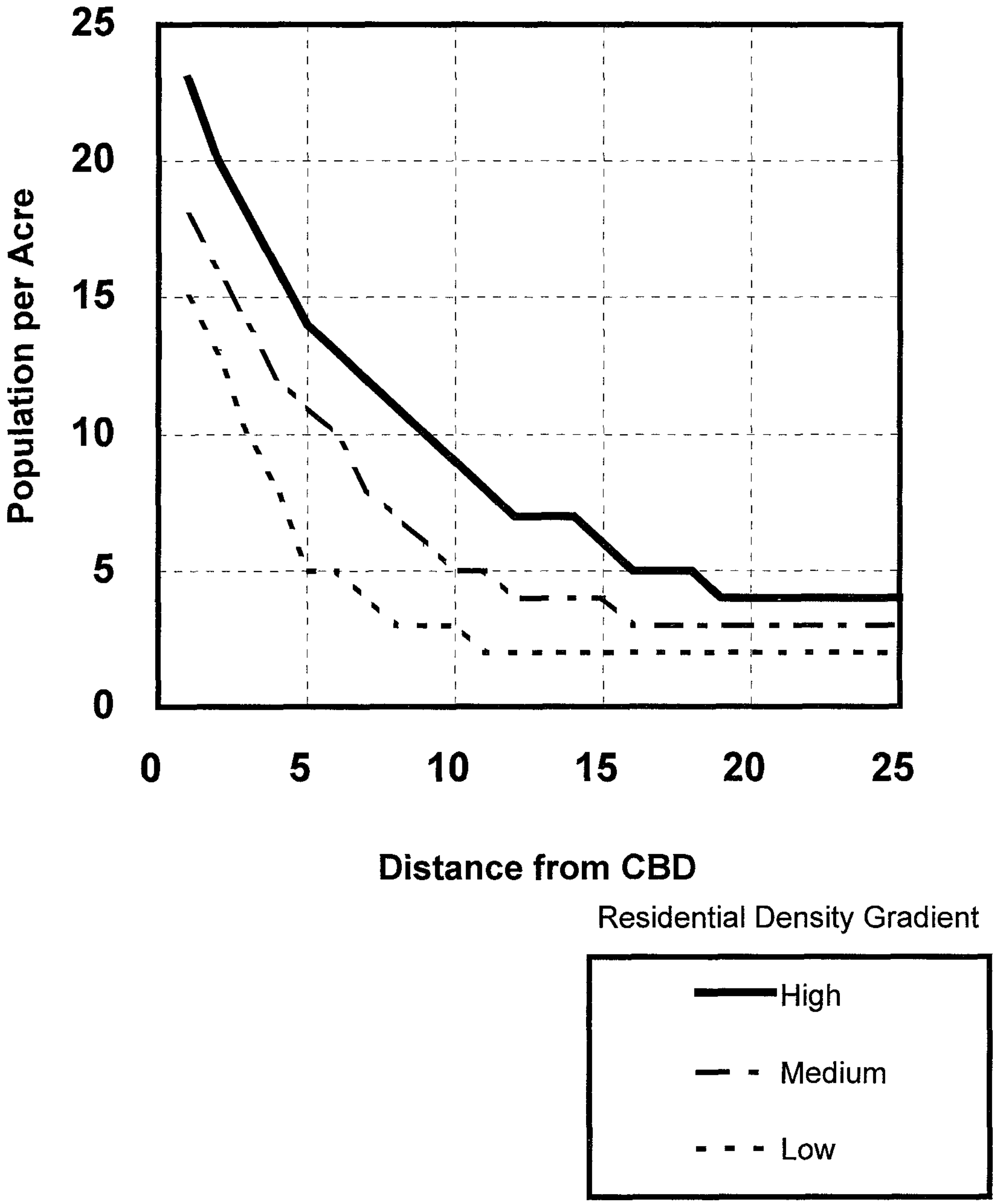


**Figure 15.
Assumed Residential Density Gradients:
Hypothetical Commuter Rail Corridors**

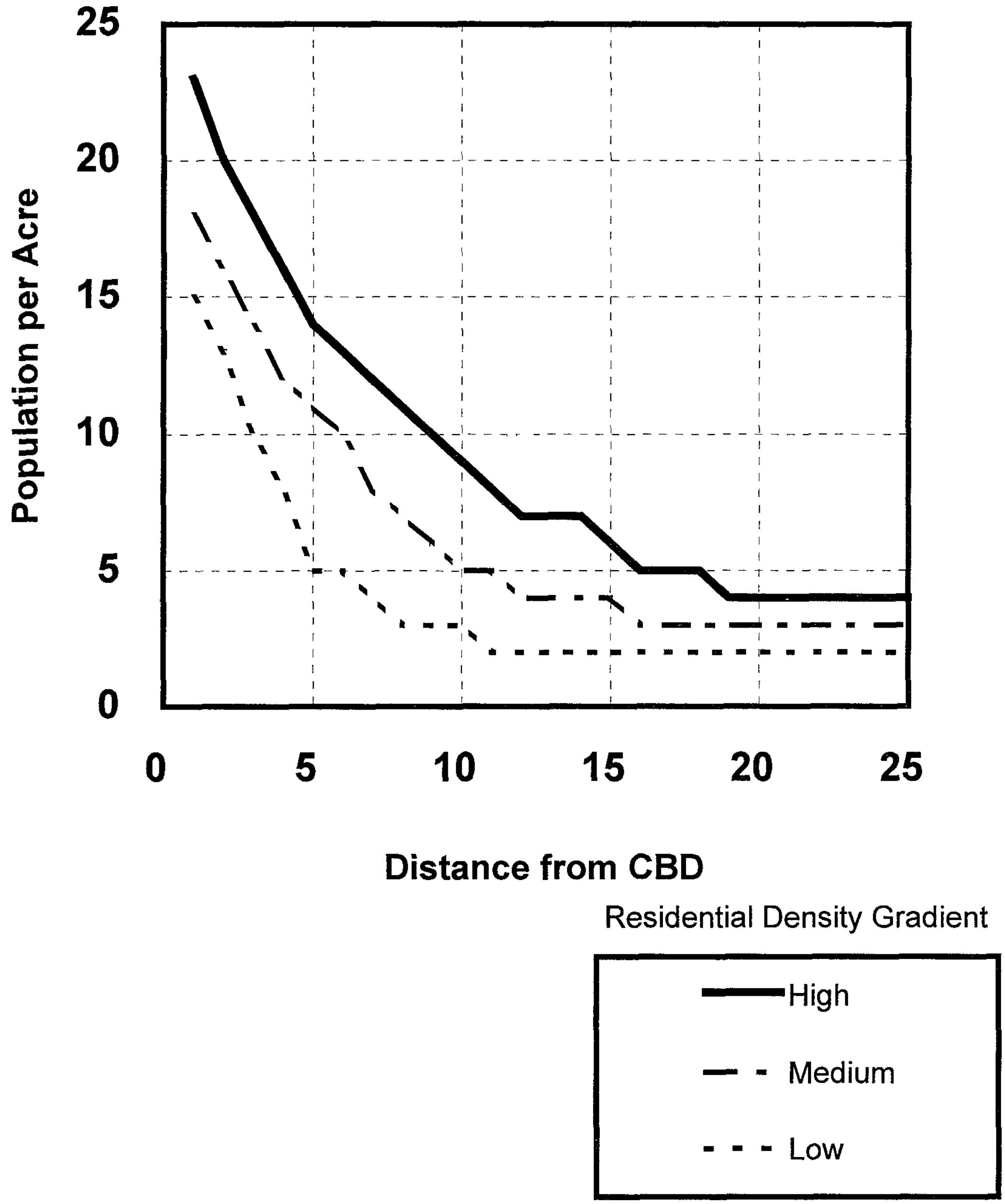
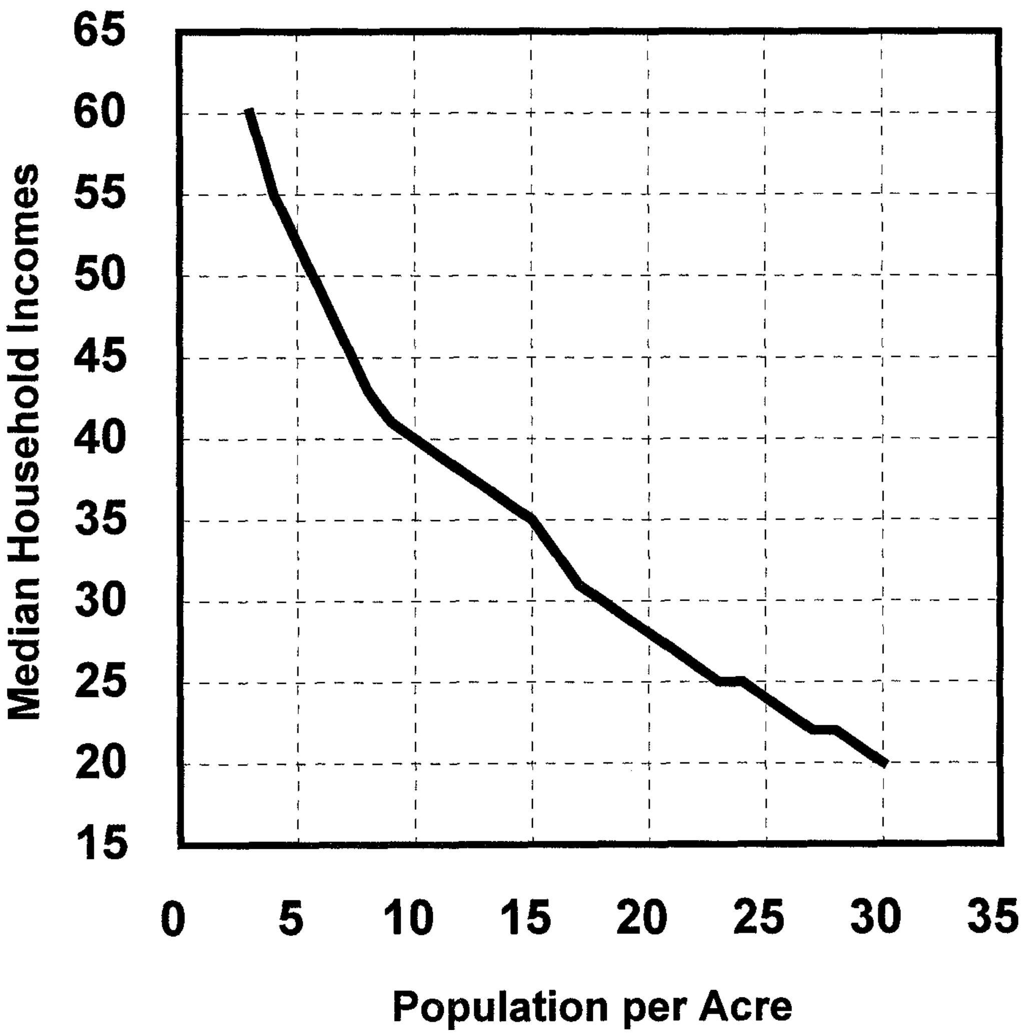


Figure 16.
Assumed Residential Density and Income:
Hypothetical Commuter Rail Corridors



For the light rail lines, route lengths of 6, 10, 15, 20, and 25 miles were tested and for the commuter rail lines lengths of 20, 30, 40, 50 and 80 miles were tested. These distances encompassed the range of line lengths found in the United States.

Station spacing for the light rail lines has been assumed for this exercise to be one mile. A test was done to examine the effect of half-mile spacing, holding all other variables constant. Because the coefficient of the station spacing variables is approximately 0.500 the impact of doubling the number of stations is to halve the ridership at each station. The effect on the ridership on the line is minimal. Put another way, within the limits of the data used to calibrate the light rail ridership model, the effect of station spacing on line ridership was small.

Station spacing for commuter rail was established as every three miles up to 12 miles from the CBD, then every two miles to 30 miles and five miles thereafter. This is consistent with station spacing patterns found in the existing commuter rail systems.

Park and ride and bus feeder patterns were established to represent average situations found in the data collected as shown in Table 12. In the data set all light rail stations within two miles of the CBD have feeder bus service and in each distance range — from two to four miles, from four to six miles, from six to eight miles, and from eight to ten miles just under half of all stations have feeder buses. In the 10 to 15 mile range about 60 of the stations had feeder bus service, and above 15 miles almost all stations did. The light rail station pattern for parking availability as a function of distance to the CBD was quite regular, increasing from none under two miles to 50 percent by 15 miles with 100 percent thereafter. An exception occurred beyond 20 miles where all the stations are in Long Beach on the Blue Line. None of them had parking available, explained by the presence of the small downtown of Long Beach.

The access pattern for commuter rail showed 84 percent of the stations within ten miles of the CBD with feeder buses, with about half the stations beyond that distance having bus access. About three-quarters of the commuter rail stations under ten miles from the CBD have parking available, and above ten miles well over 90 percent of the stations do.

For the hypothetical corridors, an average access service pattern was established matching the share of stations as a function of distance to the CBD with the data set for both feeder buses and parking. For light rail, a second pattern was established that emphasized bus feeders while de-emphasizing parking, and a third pattern emphasized parking and deemphasized feeder buses. For commuter rail, in addition to the average pattern, access mode patterns tested added bus feeders, subtracted parking, and did both. Added parking was not tested since 90 percent of the stations had parking in the average pattern, conforming to the data set. The detail on these access service patterns is described in Appendix E.

All together, daily ridership on 720 hypothetical light rail lines was calculated (eight employment sizes × two employment densities × three residential density gradients × five line lengths × three access modes patterns). For commuter rail 1,120 hypothetical patterns were tested (seven employment sizes) × (two employment densities) × (four residential density gradients) × (five line lengths) × (four access mode patterns).

Table 12. Station access Modes by Distance to the CBD

Light Rail

Distance Range	Percent Feeder Bus	Percent Parking Available
0-2	100	0
2-4	46	4
4-6	48	21
6-8	44	41
8-10	49	43
10-15	60	49
15-20	86	86
over 20	100	0

Commuter Rail

Distance Range	Percent Feeder Bus	Percent Parking Available
0-10	84	75
10-20	57	99
20-30	51	99
30-40	48	94
over 40	55	89

Source: Compiled by the authors from data provided by transit operators.

4.2 RIDERSHIP IN HYPOTHETICAL CORRIDORS

In this section a series of curves are drawn to highlight the sensitivities of daily ridership levels to the independent variables.

Light Rail

In Figure 17 the estimated daily ridership is shown for hypothetical light rail lines with the lower CBD employment density (assumes a three square mile CBD), the low residential density gradient and average access (parking and feeder bus). The exhibit shows the variation with both CBD employment and the length of the light rail line. The most striking characteristic of the graph is the exponential growth in ridership with CBD employment. This phenomenon is a result of the increase of CBD employment density when employment increases. Each higher level of CBD employment is associated with higher employment densities. At low CBD employment levels the growth in ridership does not keep pace with the increase in employment size, but at higher employment levels the slopes of the curves exceed one, and an increment of employment growth produces a greater growth in ridership.

Figure 17 also indicates the impact on ridership of the length of the light rail line. Longer line length produces a diminishing effect; a 67 percent increase in the length of the line from six to ten miles yields only about a ten percent growth in ridership. Similar diminishing returns occurs with longer line lengths.

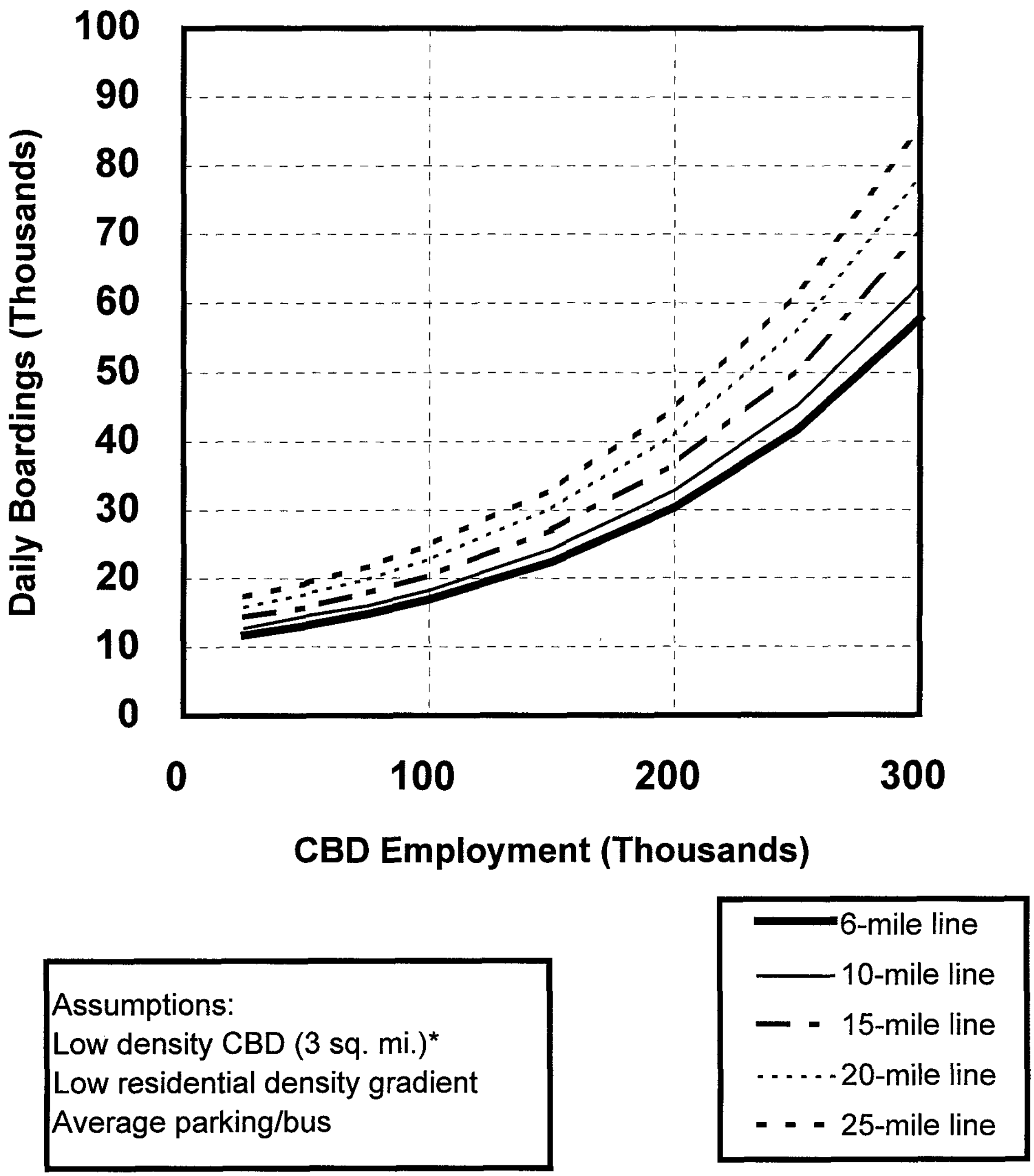
The impact of CBD employment density is isolated in Figure 18. With all else held constant (line length, access characteristics) the two square mile CBD (high employment density) and the three square mile CBD (low employment density) are compared. At the lower CBD employment levels there is hardly any impact with increased CBD employment densities, but at the high employment levels an impact begins to be noticed with the more densely developed CBD bringing more riders, upwards of 20 percent.

Figure 19 compares the impact of the residential density on ridership. The medium density residential gradient produces about 20 percent more riders than does the low density gradient, and the high gradient produces from 23 to 30 percent more riders than the medium one, with the higher percentage gains coming with the longer lines. The high density gradient produces about 50 percent more riders than the low one, again with the higher percentage gains occurring with the longer lines.

The impact of access modes provided at the light rail stations is shown in Figure 20. The addition of bus feeders with less parking availability produces a net gain in riders, while the reverse is not true. Fewer riders are likely to use the light rail line if bus feeders are lost even if parking is added. The impact of bus feeders is greater for the shorter length lines, with a 12 to 14 percent increase in ridership, but at the longer distances the loss of parking reduces the gains to only less than ten percent gain in ridership.

It appears that overall, light rail lines benefit most if they are placed in corridors with a large and dense employment concentration and in corridors with higher residential densities. Both line length and access mode characteristics will also play a role.

Figure 17.
Light Rail Daily Riders by CBD Jobs and Line Length



Assumptions:
Low density CBD (3 sq. mi.)*
Low residential density gradient
Average parking/bus

*Note:
CBD density varies with CBD employment size.

Figure 18.
Light Rail Daily Riders
by CBD Jobs and CBD Size

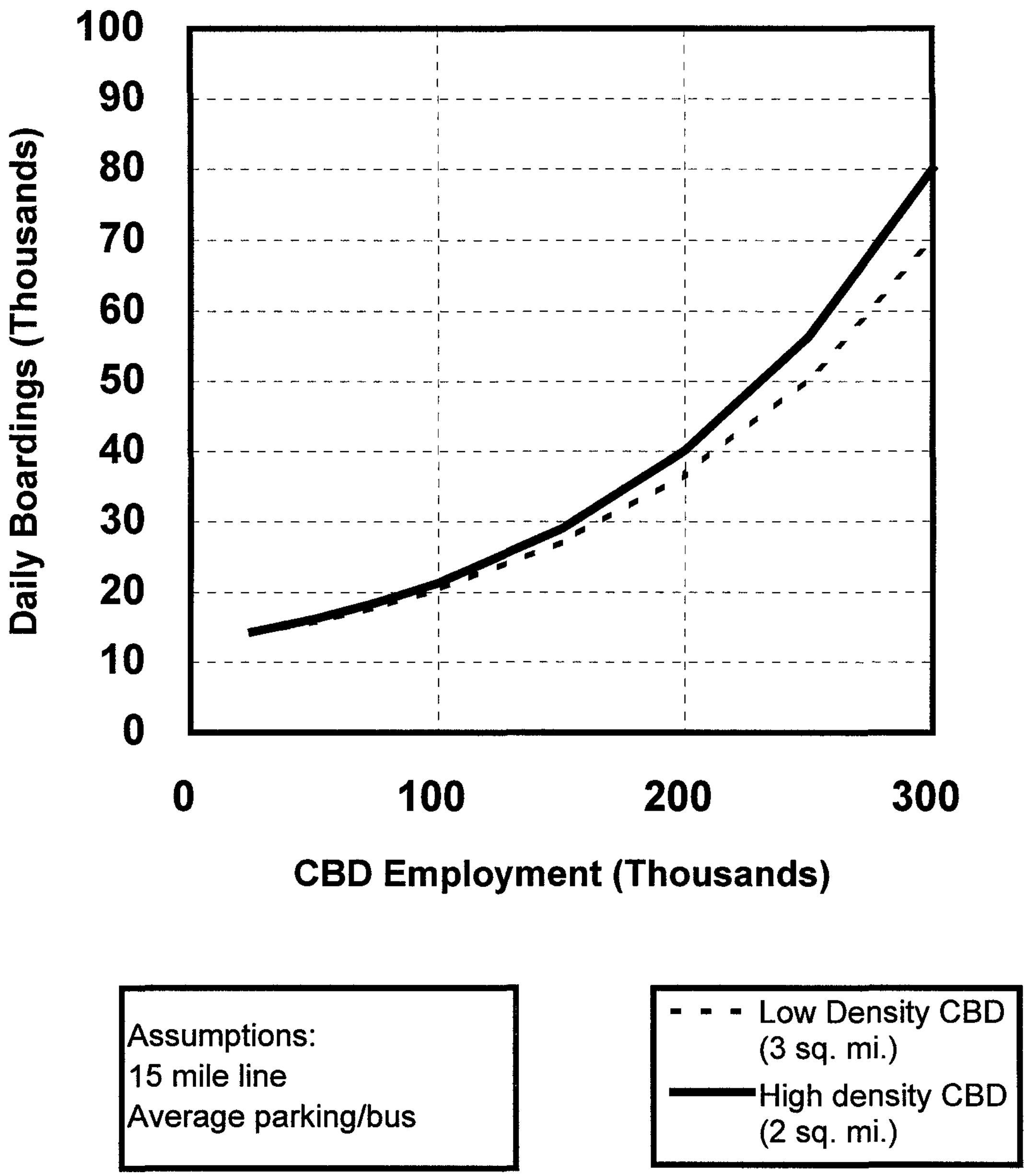


Figure 19.
Light Rail Daily Riders by Line Length and Residential Density Gradient

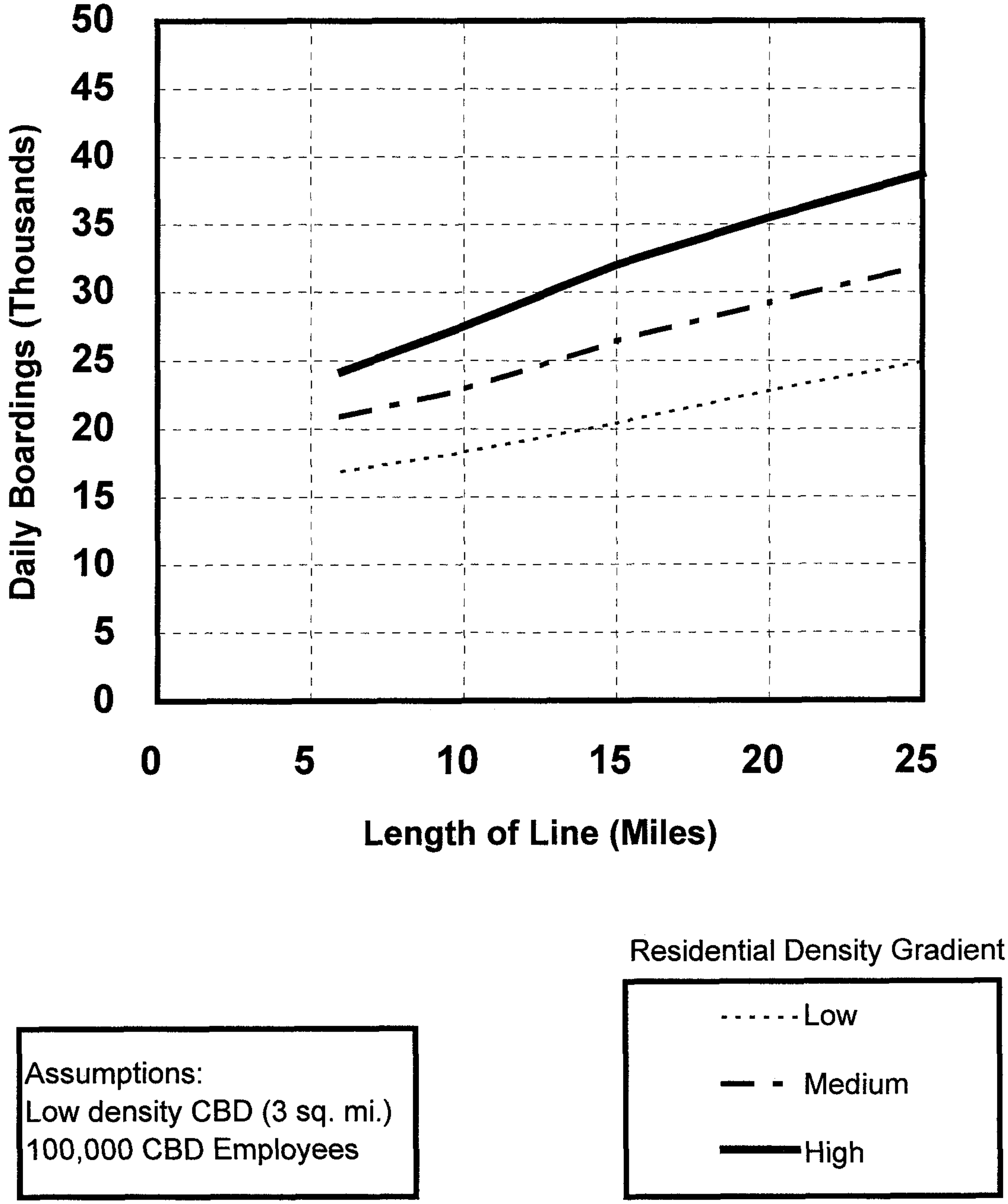
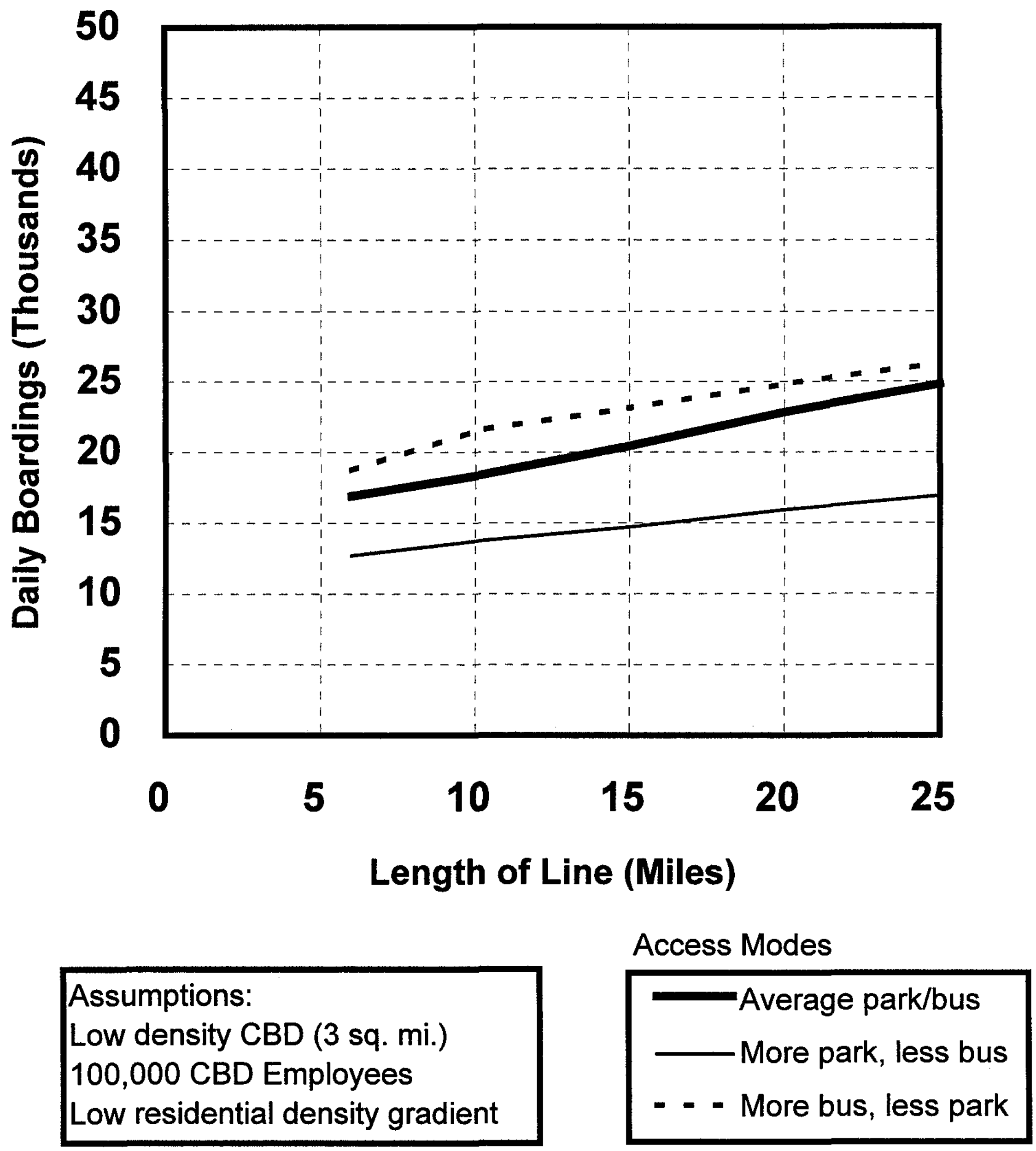


Figure 20.
Light Rail Daily Riders
by Line Length and Access Modes



Commuter Rail

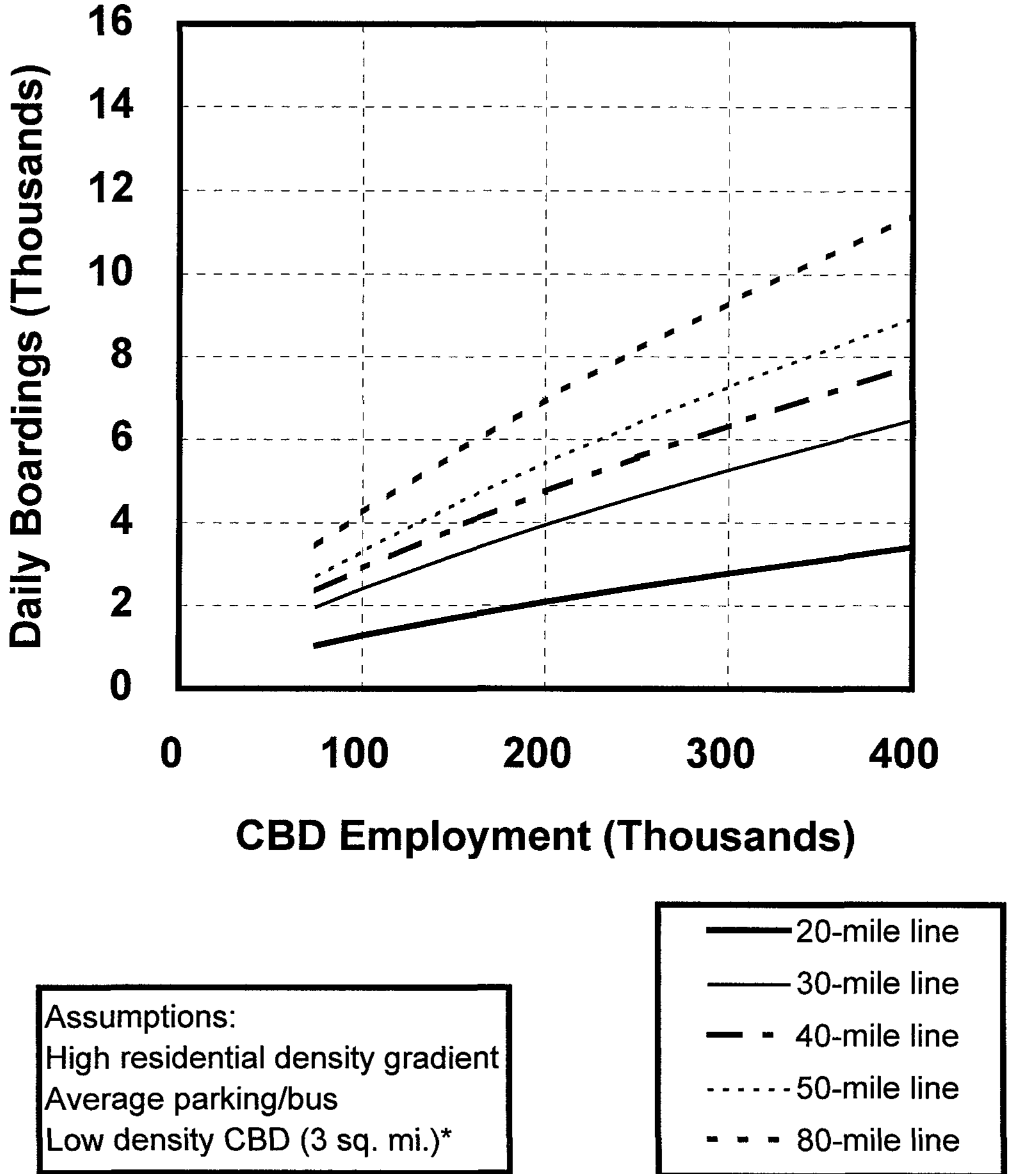
In Figure 21 and Figure 22 daily riders are plotted against the employment size for the five commuter rail line lengths tested, with Figure 21 showing the results for low employment density CBDs and Figure 22 showing them for high density CBD ridership. As expected, ridership rises significantly with employment size, increasing about three times from the 75,000 job CBD to the 400,000 job CBD, independent of line length. Each increase in CBD employment size produces a growth in ridership at a somewhat lower rate of growth than the increase in employment. This holds true for all line lengths and for both the low and high employment densities. For example, a 100 percent increase from 100,000 to 200,000 CBD jobs produces only a 58 percent growth in ridership. Recall, in contrast, that light rail ridership grew faster than employment size at the higher levels of employment.

Of course, longer line length attracts many more riders, but with diminishing returns. A 30-mile line produces 89 percent more riders than does a 20-mile line. But the increase from 30 to 40 miles in length, a 33 percent increase yields only a 20 percent gain in ridership. Similarly, increases to 50 and then to 80 miles produces a much smaller percent gains than the length of the line. This phenomenon is a result of the shape of the ridership curve with respect to distance to the CBD: commuter rail ridership grows with distance until about 35 miles and then tails off rapidly. Recall that the light rail ridership growth with line length was less, owing to the distance function in the light rail ridership equation.

In Figure 23 and Figure 24 the variation produced by the four residential density gradients are shown for two CBD employment densities — 78.1 jobs per acres and 312.5 jobs per acre, respectively. The residential density gradient has little impact in either case. It is true that the residential density variable was positive in the commuter rail ridership equation, but there are two offsetting factors. First, the income variable is positive, so higher incomes produce more riders. But the higher incomes are associated with lower densities, producing the offsetting effect. Second, within about 35 miles of the CBD the lower densities are partially offset by the growth in ridership that occur at as distances increase toward the 35 mile mark. The net effect is that for commuter rail, unlike light rail, residential density in the area of the stations is largely irrelevant to ridership, given the current strong relationship between low densities and higher incomes. Only in the limited situations where higher densities are associated with higher incomes within reasonable commuter distance by commuter rail — say 40 miles — will the positive impact of higher residential density on commuter rail be felt.

This finding should not be construed to mean that very low residential densities can support commuter rail service. After all, *some* potential riders must be living near the stations. It implies, rather, that low density areas can provide commuter rail ridership by bringing riders from a large area, especially if parking and some feeder bus service is provided to offset the small numbers within walking distances to stations.

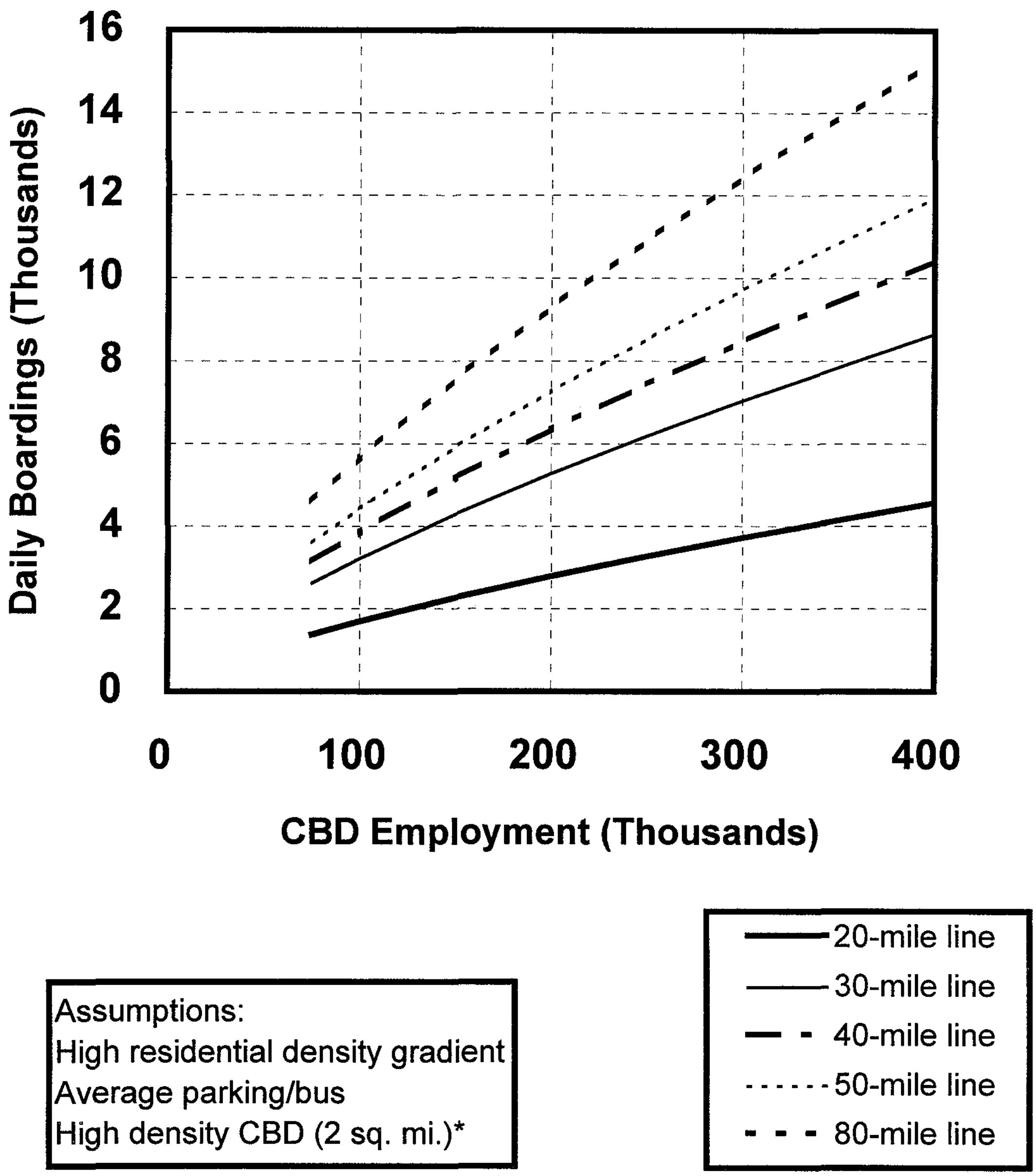
Figure 21.
Commuter Rail Daily Riders
by CBD Jobs and Line Length
(Low Density CBD)



Assumptions:
High residential density gradient
Average parking/bus
Low density CBD (3 sq. mi.)*

*Note:
CBD density varies with CBD employment size.

Figure 22.
Commuter Rail Daily Riders by CBD Jobs and Line Length (High Density CBD)

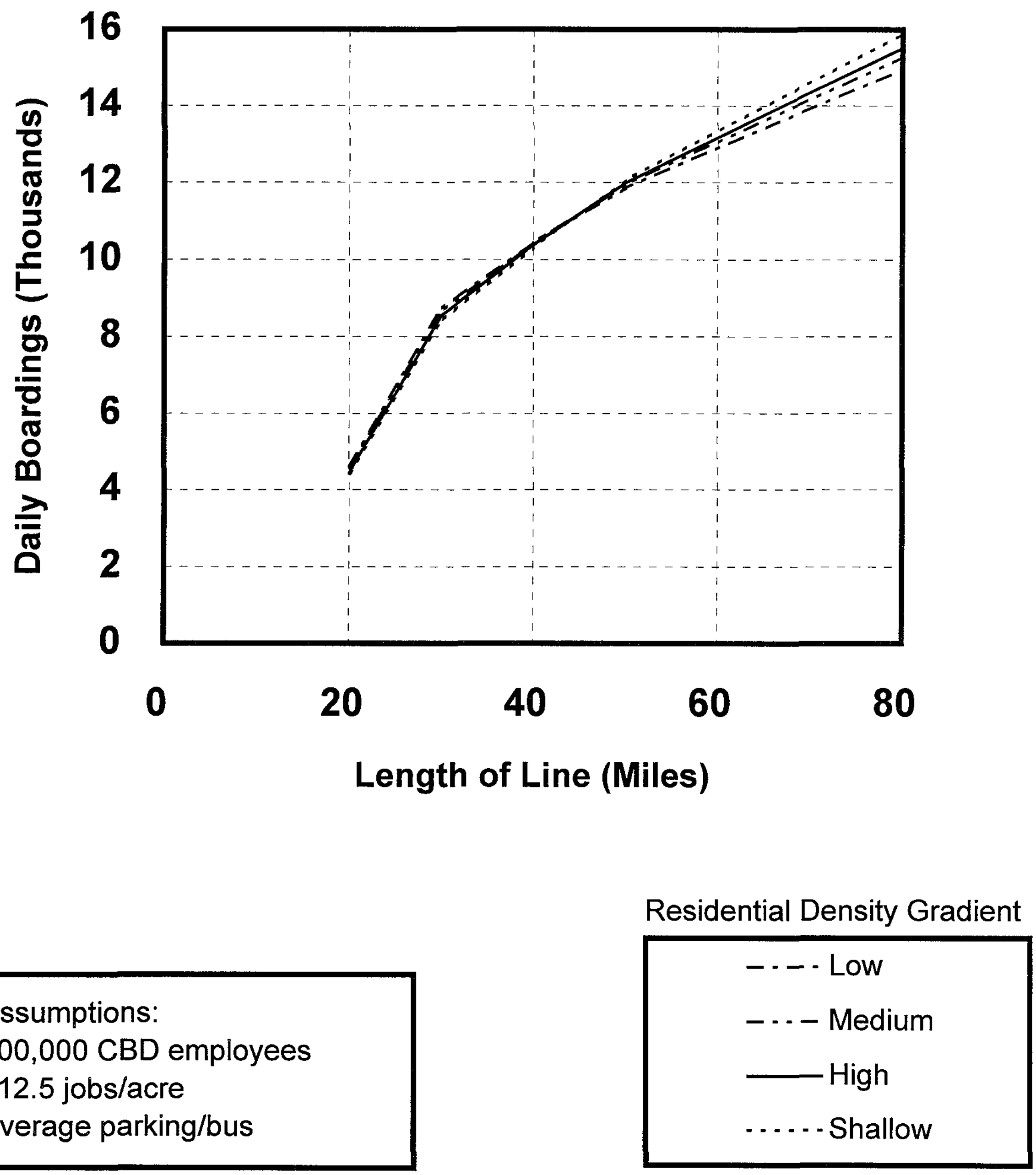


Assumptions:
High residential density gradient
Average parking/bus
High density CBD (2 sq. mi.)*

*Note:
CBD density varies with CBD employment size.

Figure 23.
Commuter Rail Daily Riders by Line Length and Residential Density Gradient (Low Employment Density)

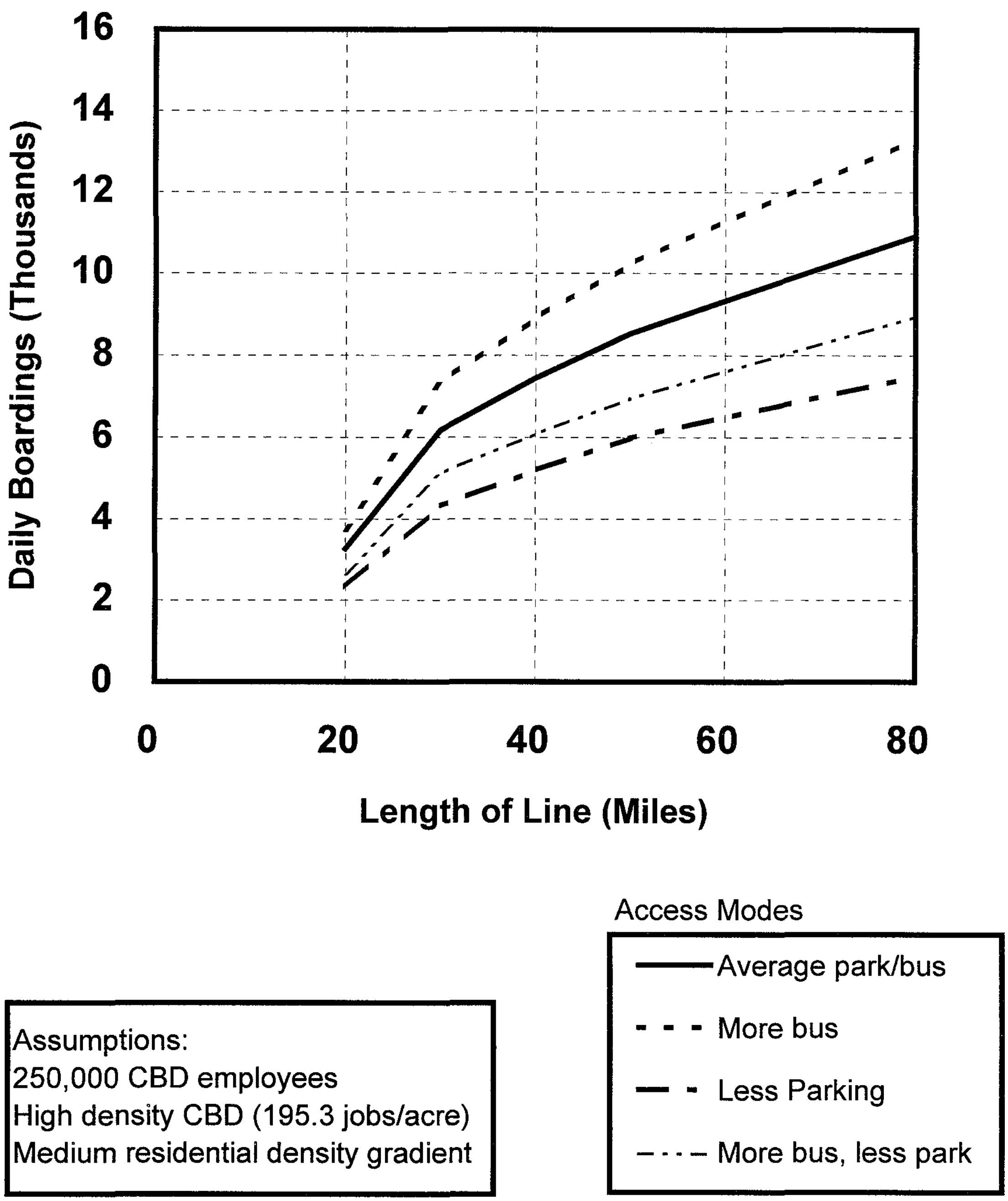
Figure 24.
Commuter Rail Daily Riders by Line Length and Residential Density Gradient (High Employment Density)



Assumptions:
400,000 CBD employees
312.5 jobs/acre
Average parking/bus

Access to the commuter rail stations does matter. In Figure 25 the four access mode patterns that were tested are shown for the medium residential pattern with an employment density of 195.3 jobs per acre (high CBD employment density with 250,000 CBD jobs). Here the addition of bus feeders above the average pattern for commuter rail boosts ridership by 15 to 22 percent, with greater percentage impact occurring at the longer distances. But the removal of parking without a substitute of bus feeders drops ridership by about 30 percent. If bus feeders are added and the parking is subtracted ridership drops only by 13 to 19 percent. This suggest strongly, as was the case for light rail, that both bus feeders and parking should be provided to bolster ridership. Of course, site specific situations and cost may not always make it possible or desirable to provide parking and bus feeders at all stations.

Figure 25.
Commuter Rail Daily Riders
by Line Length and Access Modes



Assumptions:
250,000 CBD employees
High density CBD (195.3 jobs/acre)
Medium residential density gradient

5.0 THE COST OF PROVIDING TRANSIT

In this section of this report four cost estimating models are described — operating and capital costs for both light rail and commuter rail. Each of these are estimated as a function of the characteristics and ridership of the hypothetical lines so that costs can be assigned to each of the hypothetical lines. Appendix F provides a full explanation of the cost models.

5.1 LIGHT RAIL OPERATING COST MODEL

Operating cost data for twelve light rail systems in the United States were collected for 1993. The approach was to first estimate the share of all operating costs attributable to labor, and then to determine the number of workers in the four major categories — operations of vehicles, maintenance of vehicles, maintenance of way and structures, and administration — each as a function of the system's characteristics. Labor costs are then determined using a cost per worker estimate. A separate relationship was developed for non-labor costs to fill out the operating cost picture.

For the four categories of operating costs related to the number of workers, relationships were developed using multiple regression analysis, using the number of workers in each category as the dependent variable. These relationships are summarized in Table 13.

By adding each of these four equations together the total number of workers is estimated. Then, using an average cost per worker, inclusive of benefits, estimated in 1993 dollars as $66,004, an annual cost for labor is estimated. Once the non-labor costs are added, annual light rail operating costs is estimated.

To account for the non-labor costs, mostly for the cost of energy, the relationship of non-labor costs with annual vehicle-miles was examined. Fully, 63 percent of the variation in non-labor costs can be explained by annual revenue vehicle-miles. The relationship is:

Non-labor cost ($ million) = 1.342 + (1.441 × annual revenue vehicle-miles (millions))

Collecting the terms from the labor and non-labor portions of the operating cost model produces the following expression:

Summary Formula for Light Rail Transit O&M Labor Requirements:	-107.75	+	0.492	×	Annual Revenue Hours of Service × 1,000
		+	3.85	×	Number of Track Miles
		+	35.61	×	Number of Track Miles per Vehicle in Fleet
		+	1.93	×	Number of Vehicles in Maximum Service
		+	0.884	×	Number of Vehicles in Fleet
		+	0.667	×	Annual Revenue Miles (in 1,000s) per Vehicle in Fleet
		+	-2.81	×	Average Vehicle Speed (mph)
		+	61.41		If Average Station Spacing is Less than 1/2 mile.

Summary Formula for Light Rail
Transit O&M Labor Costs (1993 $) = $66,004 × Total Light Rail O&M Labor Requirements

Where $66,004 is the Average O&M Labor Cost per Worker (1993 Dollars, Geographic Cost of Living Normalized)

Table 13. Number of Light Rail Workers as Function of System Characteristics

	Labor Cost Component			
System Characteristic	Vehicle Oper.	Vehicle Maint.	Maint. of Way	Admin.
Vehicles in maximum service	1.93			
Annual rev.-hrs (000's)	0.280	0.212		
Vehicle speed	-2.81			
Vehicles in fleet		0.884		
Track-mi. per veh. in fleet		35.61		
Station spacing *			61.41	
Annual rev-mi. (000's) per vehicle in fleet				-0.667
Track-miles			3.02	0.826
Constant	31.13	-43.24	-64.54	-31.39
Adjusted R-squared	0.965	0.926	0.809	0.785

* If average spacing is less than 0.5 miles add this term. Workers for maintenance of way includes dummy variable for Philadelphia since SEPTA maintains right-of-way not owned by them.

5.2 LIGHT RAIL CAPITAL COST MODEL

Capital cost data was collected by components for eight of the 12 light rail systems for which there was operating cost data. The four systems omitted were deemed to be too old for their capital costs to be representative of current or prospective conditions. An equation was then derived by determining an average cost for each of the cost elements using data from the eight systems. It was based on assuming an average mix of track-miles and stations by type of elevation (grade, elevated, subway). To account for lines that might deviate substantially from that average a second equation was also developed that includes components to account for portions of the right-of-way and stations that are likely to cost either much more or much less than the average mix because of the line's elevation. Typically, elevated segments cost more than the average, subway segments much more than the average, and at-grade segments less than the average. Average values for components of light rail costs were estimated on either a cost per track-mile, a cost per route-mile or a cost per vehicle basis. The two equations are presented below.

Capital costs (in 000s of 1993 $) for light rail =
$1.41 \times (6{,}440 \times$ track-miles
$+ 1{,}220 \times$ number of stations
$+ 1{,}920 \times$ vehicles in fleet)

Capital costs (in 000s of 1993 $) for light rail =
1.41 × (2940 × track-miles
+ 2,350 × at-grade track-miles
+ 6,250 × elevated track-miles
+ 25,680 × subway track-miles
+ 160 × number of stations
+ 890 × number of at-grade stations
+ 5,440 × number of elevated stations
+ 40,860 × number of subway stations
+ 1,920 × number of vehicle in fleet)

The factor of 1.41 accounts for the ancillary costs of project management, planning studies, engineering and design, construction management, testing and start-up, insurance, finance fees, and other non-capital expenditures associated with putting the line of system in place.

For systems with a fleet of greater than 50 vehicles the cost per vehicle is likely to be less. It will be assumed in the hypothetical examples that the cost per vehicle term in the equations above will be $1800 or $1.8 million per vehicle.

5.3 CALCULATION OF LIGHT RAIL COST FOR HYPOTHETICAL LINES

Each of the variables that are input to the light rail operating cost and capital cost models can be calculated for any hypothetical light rail line based on ridership and the characteristics assumed for the line. The calculation for each of input variables for the light rail operating and capital cost models is described below.

The number of **vehicles in maximum service** is a function of the level of ridership crossing into the CBD (assumed to the maximum load point) in the peak hour, the length of the line, the capacity of a vehicle, and the average speed of the line. Peak hour ridership is assumed to equal to 22 percent of the daily one-way ridership. This is based on the average of 21.6 percent for the three light rail systems for which this data was available, and 22.3 percent for the average of five light rail systems' data collected in the 1970s and reported in <u>Urban Rail in America</u>. The daily one-way ridership is assumed to equal the sum of the boardings at each non-CBD station. Therefore, the vehicle in maximum service is given by the equation:

Vehicles in maximum service = (boardings × 0.22 × line length × 2) / (75 × 17),

Where the capacity of the vehicle is assumed to be 75 riders per vehicle and the speed of the vehicles, including layover time, is assumed to be 17 miles per hour.

The **number of vehicles in the fleet** is assumed to be 20 percent greater than the number of vehicles in maximum service.

The **annual vehicle-miles** are calculated by first determining the peak hour vehicle-miles, which is equal to the vehicles crossing into the CBD in the peak hours × the line length × 2, and then multiplied by a daily factor and an annual factor. The daily factor is developed by assuming that the line operates 18 hours per day, with the four hours surrounding the two peak hours operating at 80 percent of the peak hour frequency, ten other hours operate at half the frequency of the peak hour, an the remaining two hours operate at 30 percent of the peak hour frequency. Taken together this converts to a daily peak hour factor of 10. The annual vehicle-mile factor assumes that Saturdays operate at 50 percent of the service level of a weekday and that Sundays and holidays operate at 30 percent of weekday service levels. The annual vehicle-miles is given by the equation:

Annual vehicle-miles = ((boardings $\times$ 0.22 $\times$ line length $\times$ 2) / 75) $\times$ 10 $\times$ 295,

where 10 is the assumed ratio of daily to peak hour vehicle-miles, and 295 is the assumed ratio of annual to daily vehicle-miles.

Annual vehicle-hours is equal to the annual vehicle-miles divided by the average speed.

Each hypothetical line is assumed to be two-tracked, so that the number of **track-miles** are equal to two times the line length, including the line segment within the CBD.

Station spacing is assumed to be one mile for all the hypothetical lines.

The **number of stations** is assumed to equal the length of the hypothetical line. For high density CBDs two more stations are added and for low density CBDs three are added.

Once these values are calculated for each hypothetical light rail line, the operating and capital cost models can be applied directly.

5.4 COMMUTER RAIL OPERATING COST MODEL

The operating cost model for commuter rail was established in the same manner as was the light rail model. Data from 16 systems was collected. Unfortunately, for many of the systems only partial data was available. For example, of the 16 only 11 had data on the number of workers assigned to various categories. In other cases the allocation of costs was confused because of the contracting out of some services or accounting idiosyncrasies. Nevertheless, an attempt was made to develop an operating cost model that separately accounted for the major categories of workers with the intent of modeling the number of workers in each category, applying a cost per worker and then adding to it a separate non-labor cost component. Details are provided in Appendix F.

A summary of the four equations for number of workers by category for commuter rail is presented in Table 14.

With the relationships for the four worker categories in place, they are summed and the total multiplied by the average cost per worker to get labor costs. For the six commuter rail systems with credible cost per worker data, the average was just over $60,000. A seventh, the Long Island Rail Road was $85,600 and was not included.

Labor costs as a percent of all operating costs averaged 71 percent for the seven systems. Two others were not included since their non-labor costs shares were either very high (96 percent) or low (45 percent), and are likely a result of contracting out or accounting practices.

Table 14. Number of Commuter Rail Workers As Function of System Characteristics

	Labor Cost Component			
System Characteristic	Vehicle Oper.	Vehicle Maint.	Maint. of Way *	Admin.
Annual rev.-hrs (000's)	1.351			
Vehicles in fleet		1.265		
Track-miles			*	
Annual veh-mi. (000's) per track-mile			*	
Non-administrative workers				0.250
Constant	30.45	0.0	*	0.0
Number of observations	10	9	10	10
Adjusted R-squared	0.959	0.973	0.821	0.969

* For the regression for the maintenance of way and structures workers the square root of the number of workers was used as the dependent variable and two variables, track-miles and vehicle-miles per track-mile were not transformed. Thus, the equation to be used to calculate the number of workers has the entire expression (-1.109 + 0.020 × track-miles + 0.302 × annual vehicle-miles per track-miles) squared.

Taken together, the commuter rail operating cost relationships produced the following equation:

Summary Formula for Total Commuter					
Rail Transit O&M Labor Requirements:	1.25 × {		30.542		
		+	1.351	×	Annual Revenue Hours of Service (in 1,000a)
		+	1.265	×	Number of Vehicles in Fleet
		+ (	-1.109		
		+	0.020	×	Number of Track Miles
		+	0.302	×	Annual Revenue Miles (in 1000s) per Track Mile
Summary Formula for Total Commuter					
Transit O&M Labor Costs =	$66,004	×	Total Light Rail O&M Labor Requirements		

Where $66,004 is the Average O&M Labor Cost per Worker (1993 Dollars)

5.5 COMMUTER RAIL CAPITAL COST MODEL

Commuter rail capital costs are very difficult to estimate, given the unique situation for each existing system. Instead of trying to compile empirical data from individual systems, per unit cost estimates of each capital cost element were made, based on the files of Parsons Brinckerhoff. These are presented in Table 15. From Table 15, the cost components with identical units can be combined, yielding the following equation:

Capital cost (in 000's of 1993 $) for commuter rail = 1.24 × (2,787 × route-miles + 1,843 × number of vehicles in fleet + 7,510 × number of stations)

where the 1.24 factor accounts for the ancillary costs of project management, planning studies, engineering and design, construction management, testing and start-up, insurance, finance charges, and other non-capital expenditures associated with putting the line of system in place.

5.6 CALCULATION OF COMMUTER RAIL COST FOR HYPOTHETICAL LINES

Each of the variables that are input to the commuter rail operating cost and capital cost models can be calculated for any hypothetical commuter rail line based on ridership and the characteristics assumed for the line. The calculation for each of input variables for the light rail operating and capital cost models is described below.

The number of **vehicles in maximum service** is a function of the level of ridership crossing into the CBD (assumed to be the maximum load point) in the peak hour, the length of the line, the capacity of a vehicle, and the average speed of the line. To calculate the peak hour ridership it is assumed that it is equal to 30 percent of the daily one-way ridership. The daily one-way ridership is assumed to equal the sum of the boardings at each non-CBD station. Therefore, the vehicle in maximum service is given by the equation:

Vehicle in maximum service = (boardings × 0.30 × line length × 2) / (120 × speed),

where the capacity of the vehicle is assumed to be 120 riders per vehicle and the speed of the vehicles, including layover time, is assumed to vary by line length as follows:

For 20-mile line, speed is 32 miles per hour;
For 30-mile line, speed is 35 miles per hour;
For 40-mile line, speed is 37 miles per hour;
For 50-mile line, speed is 40 miles per hour; and
For 80-mile line, speed is 43 miles per hour.

The **number of vehicles in the fleet** is assumed to be 20 percent greater than the number of vehicles in maximum service.

Table 15. Commuter Rail Conceptual Capital Cost Estimates by System Components

Commuter Rail Capital Component		*Unit of Measure*	*Unit Cost (1993 $)*
1	**Trackwork Improvements**		
	Resurface Existing Mainline	Track Mile	$ 120,000
	Realign/Relocate Existing Tracks	Track Foot	$ 70
	Construct New Mainline	Track Foot	$ 140
	Extend/Add Siding/Teamtracks	Track Foot	$ 140
	Add New Crossover/Turnout	Each	$ 180,000
	Remove Existing Crossovers/Turnouts	Each	$ 15,000
	Add Power Switches	Each	$ 150,000
	Average Cost for Trackwork Improvements	Route Mile	$ 1,465,000
2	**Stations & Parking**	Each	$ 7,510,000
3	**CTC, Signals and Crossing Protection**		
	Add New Gates, Signal & Signage	Each	$ 175,000
	Upgrade/Adjust Existing Gates, Signals & Signage	Each	$ 60,000
	CTC Additions & Modifications	Route Mile	$ 264,000
	Average Cost for CTC, Signal and Crossing Protection	Route Mile	$ 520,000
4	**Site Improvements**		
	Upgrade Existing Structures	Route Foot	$ 2,200
	Replace Single Track Structures	Route Foot	$ 10,920
	Construct New Structures	Route Foot	$ 10,920
	Drainage Improvements	Route Mile	$ 60,000
	Access Improvements	Route Mile	$ 20,000
	Average Cost for Site Improvements	Route Mile	$ 652,000
5	**Maintenance and Storage Facilities (Incl. Layovers)**	Per Vehicle	$ 430,000
6	**Right of Way**	Route Mile	$ 150,000
7	**Rolling Stock**		
	Locomotives	Each	$ 1,660,000
	Coaches – Single Level	Each	$ 1,320,000
	Coaches – Bi-Level	Each	$ 1,770,000
8	**Agency Cost**		
	(Administration, Project Management, Engineering & Design, Construction Management, Design Support, Training, Testing & Start-Up, Insurance, Finance Charges and Other)	24% of Items 1 through 7 (Must Be Calculated)	
	System Average Cost	Route Mile	$ 5,800,000

Source: Parsons Brinckerhoff Capital Cost Reference Materials

The **annual vehicle-miles** is calculated by first determining the peak hour vehicle-miles, which is equal to the vehicles crossing into the CBD in the peak hours × the line length × 2, and then multiplied by a daily factor and an annual factor. The daily factor is developed by assuming that the line operates 18 hours per day, with the four hours surrounding the two peak hours operating at 80 percent of the peak hour frequency, ten other hours operate at half the frequency of the peak hour, an the remaining two hours operate at 30 percent of the peak hour frequency. Taken together this converts to a daily peak hour factor of 10. The annual vehicle-mile factor assumes that Saturdays operate at 50 percent of the service level of a weekday and that Sundays and holidays operate at 30 percent of weekday service levels. The annual vehicle-miles is given by the equation:

Annual vehicle-miles = [((boardings × 0.30 × line length × 2) / 120)] × 10 × 295,

where 10 is the assumed ratio of daily to peak hour vehicle-miles, and 295 is the assumed ratio of annual to daily vehicle-miles.

Annual vehicle-hours is equal to the annual vehicle-miles divided by the average speed, determined as a function of the line length as indicated above.

Each hypothetical line is assumed to be two-tracked, so that the number of **track-miles** is equal to two times the line length.

The **number of stations** was determined by the assumptions made for the hypothetical commuter rail lines. These are;

For 20-mile line, there are 9 stations;
For 30-mile line, there are 14 stations;
for 40-mile line, there are 19 stations;
For 50-mile line, there are 21 stations; and
For 80-mile line, there are 27 stations.

The number of stations includes a terminal station in the CBD.

Once these values are calculated for each hypothetical commuter rail line, the operating and capital cost models can be applied directly.

The steps to calculate operating costs for light rail and commuter rail are presented in the form of flow charts in Figure 26 and Figure 27.

Figure 26.
Flow Chart for Calculating Light Rail Operating Costs

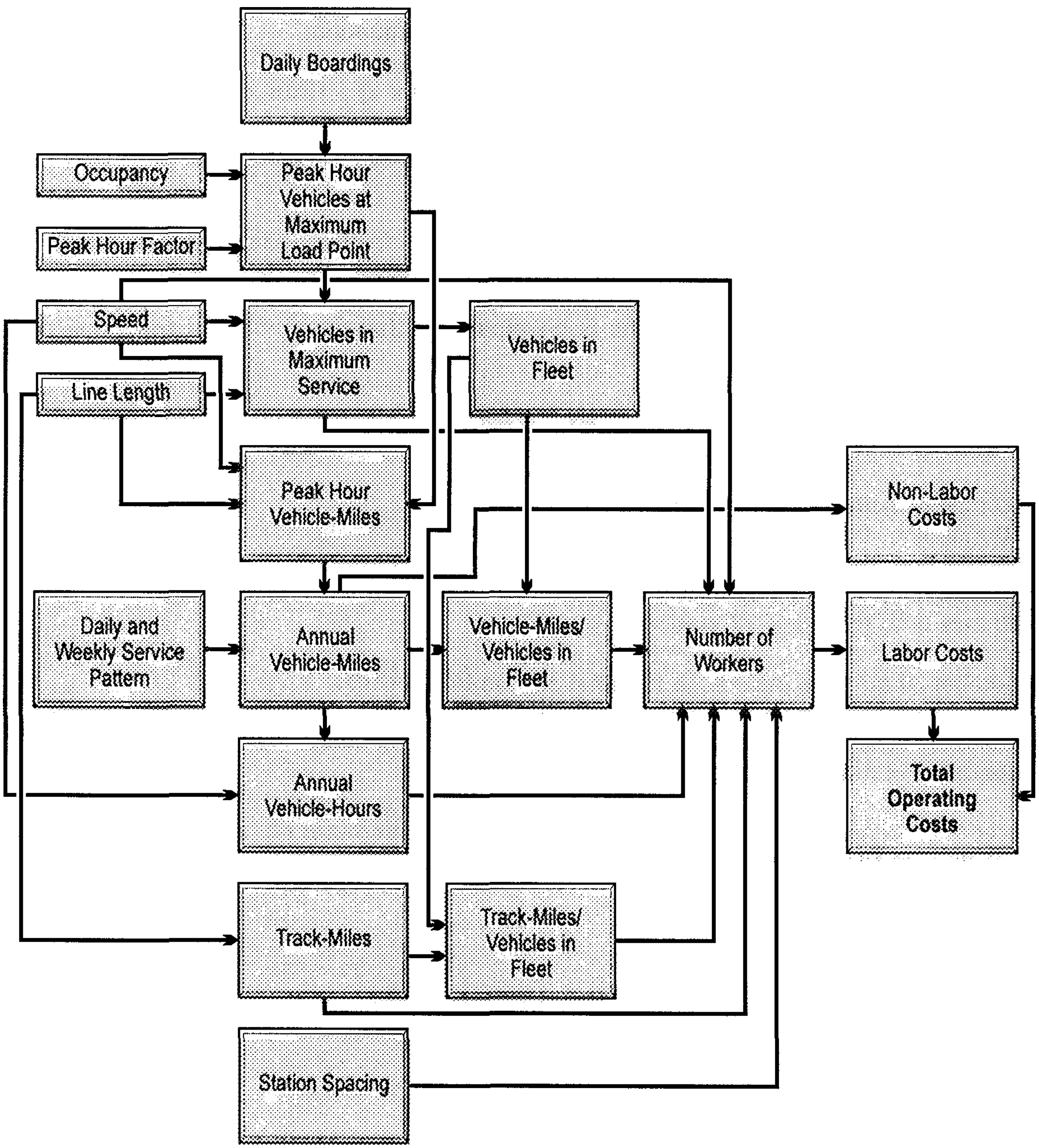
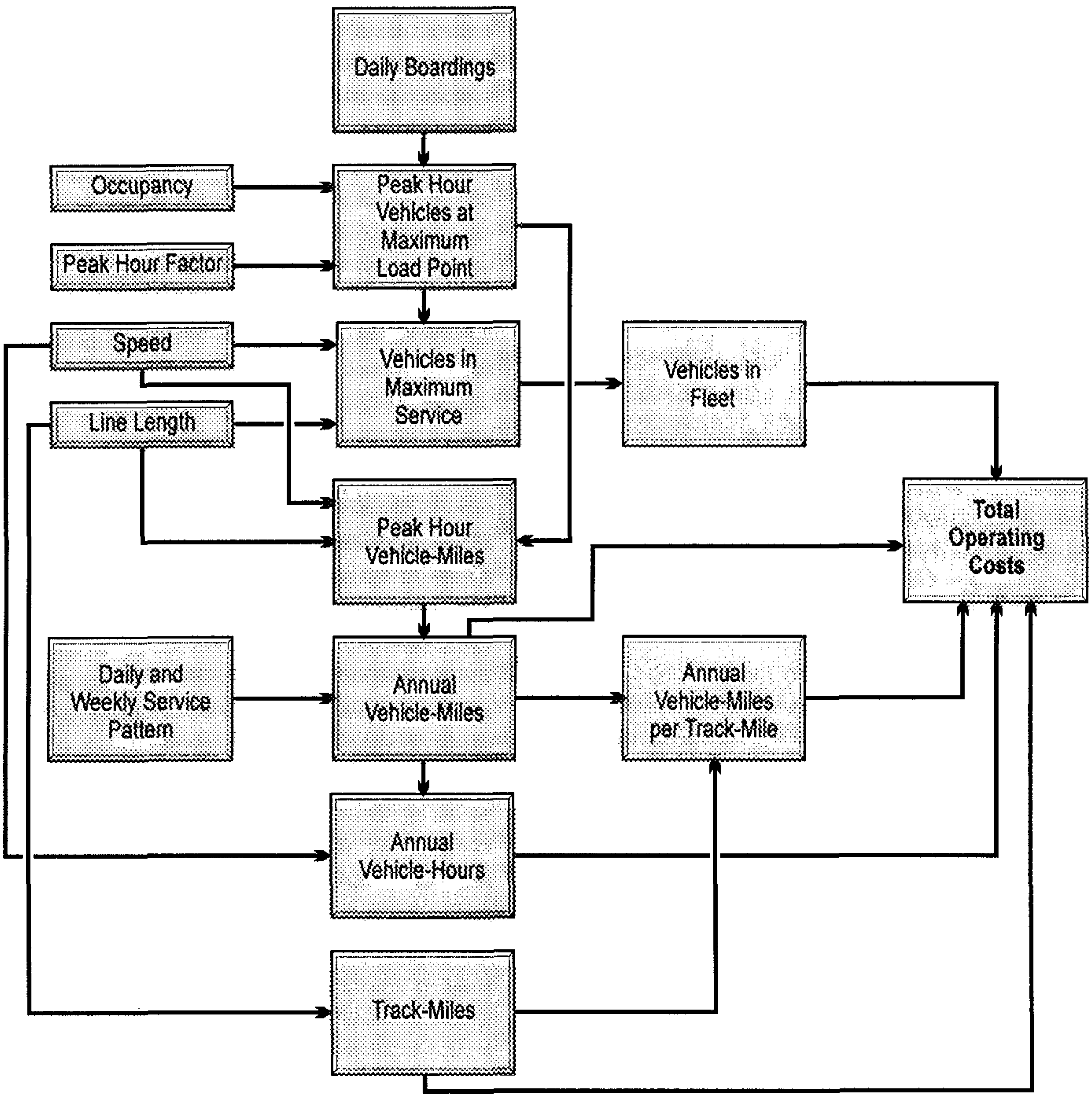


Figure 27.
Flow Chart for Calculating Commuter Rail Operating Costs



6.0 HYPOTHETICAL CORRIDOR COSTS

With the cost models in place the costs for each of the hypothetical corridors postulated earlier in Section 4.0 are calculated. A few words of caution are in order. Operating costs are based on the best estimated of average costs and can vary widely depending on local conditions of wage rates, labor agreements, and operating rules. The operating cost associated with bus feeders are not accounted for in the cost analyses, nor are the operating costs avoided by replacing bus routes with rail lines.

For light rail lines with high ridership, the large number of vehicles needed in the peak hour may be linked in trains, while still providing high frequency service. For example, if 60 vehicles are needed to carry the peak hour load across the maximum load point, it would be logical to operate them in 20 three-car trains, still maintaining an excellent three-minute headway, and saving operating costs with fewer drivers. Hence, the operating costs of high ridership lines may be overestimated here.

On the capital side costs can vary from the per unit averages presented here, particularly if there are significant lengths of right-of-way elevated or in tunnel. The capital costs associated with the provision of parking in excess of the specifications in Appendix F) can also drive up the costs of lines, especially if the parking is in structures.

6.1 LIGHT RAIL COSTS

In Figure 28 through Figure 31 the annual operating costs for the hypothetical corridors are shown as a function of the land use variables discussed in the report — CBD employment, CBD size, and residential density gradients, and by line length and access mode. In Figure 28 the annual operating cost is shown for the five line lengths — 6, 10, 15, 20, and 25 miles, as a function of CBD employment. Higher CBD employment drives the growth in ridership, which, in turn, requires more vehicles and the workers to operate and maintain them, increasing operating costs. The line length, meanwhile adds to the operating cost too, with more riders and with more workers who are needed to maintain the right-of-way. The combination of high CBD employment and long line length begins to be felt in the upper right portion of the exhibit.

In Figure 29 the effects of CBD employment density on annual operating costs are shown for a 15-mile light rail line. The effects of higher density are not felt for lower CBD employment levels. This is because the costs associated with the higher ridership that is generated by the higher employment density is offset by the shorter distance the line must operate in the CBD to pick up riders. As employment levels rise, the increase in costs associated with higher ridership in high density CBDs is not offset by the costs savings for the shorter line length assumed for the high employment density CBD.

Residential density's impact on light rail operating costs is depicted in Figure 30. (The reader should refer back to Section 4.1 to see how the residential density gradients used for light rail corridors were defined.) As expected, costs increase with the higher residential density gradients.

Figure 28.
Light Rail Operating Costs by CBD Jobs and Line Length

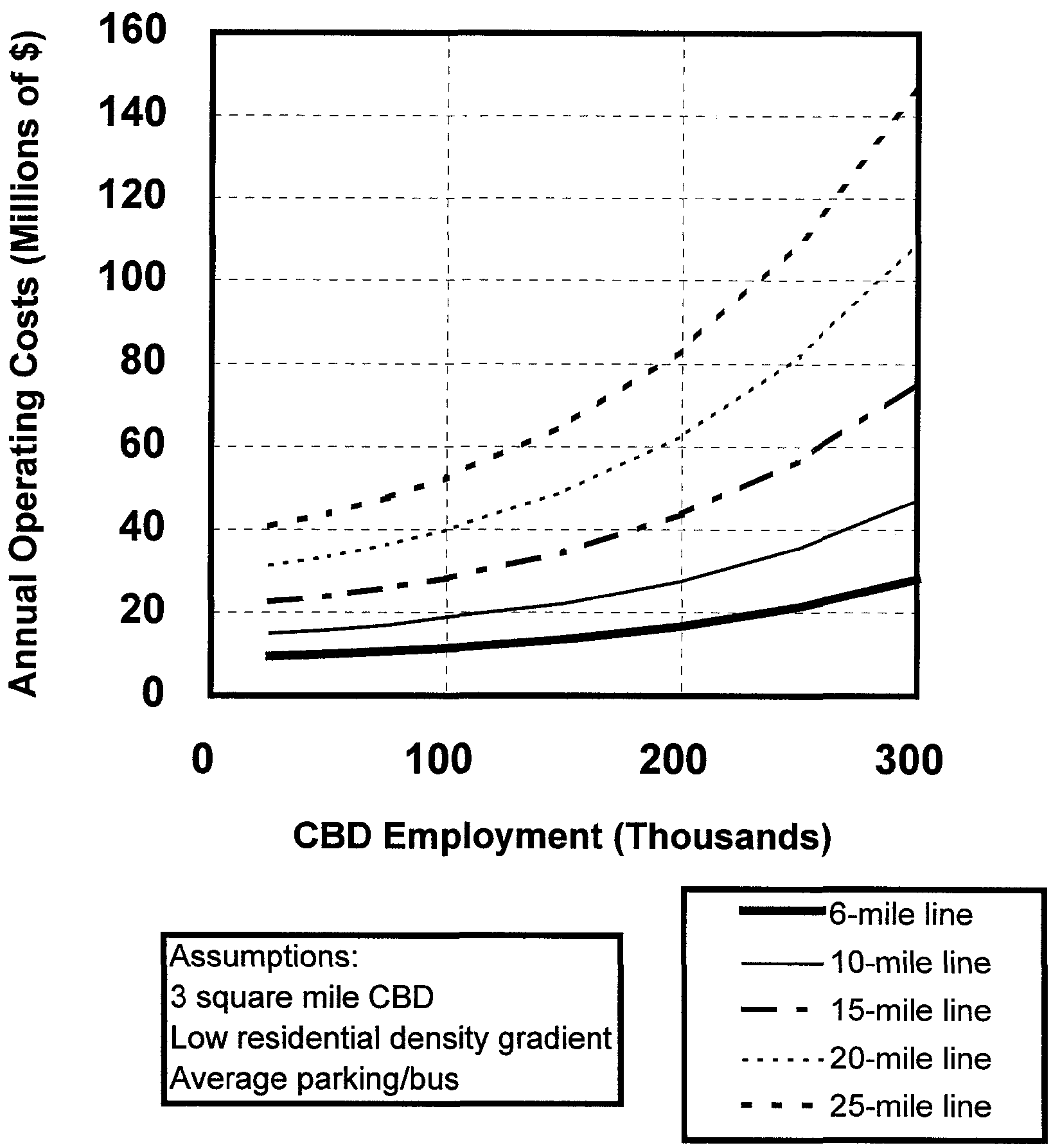


**Figure 29.
Light Rail Operating Costs
by CBD Jobs and CBD Size**

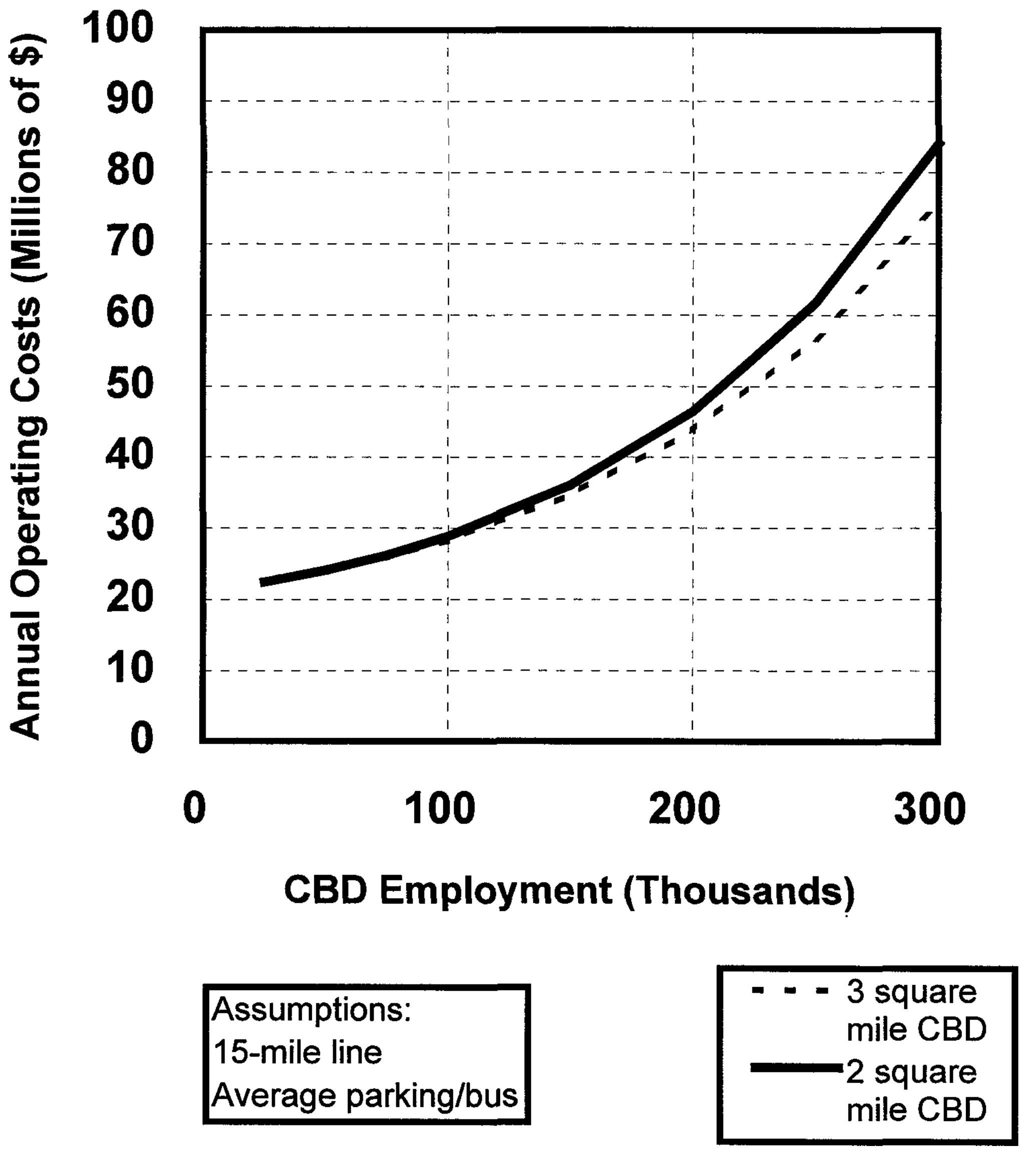
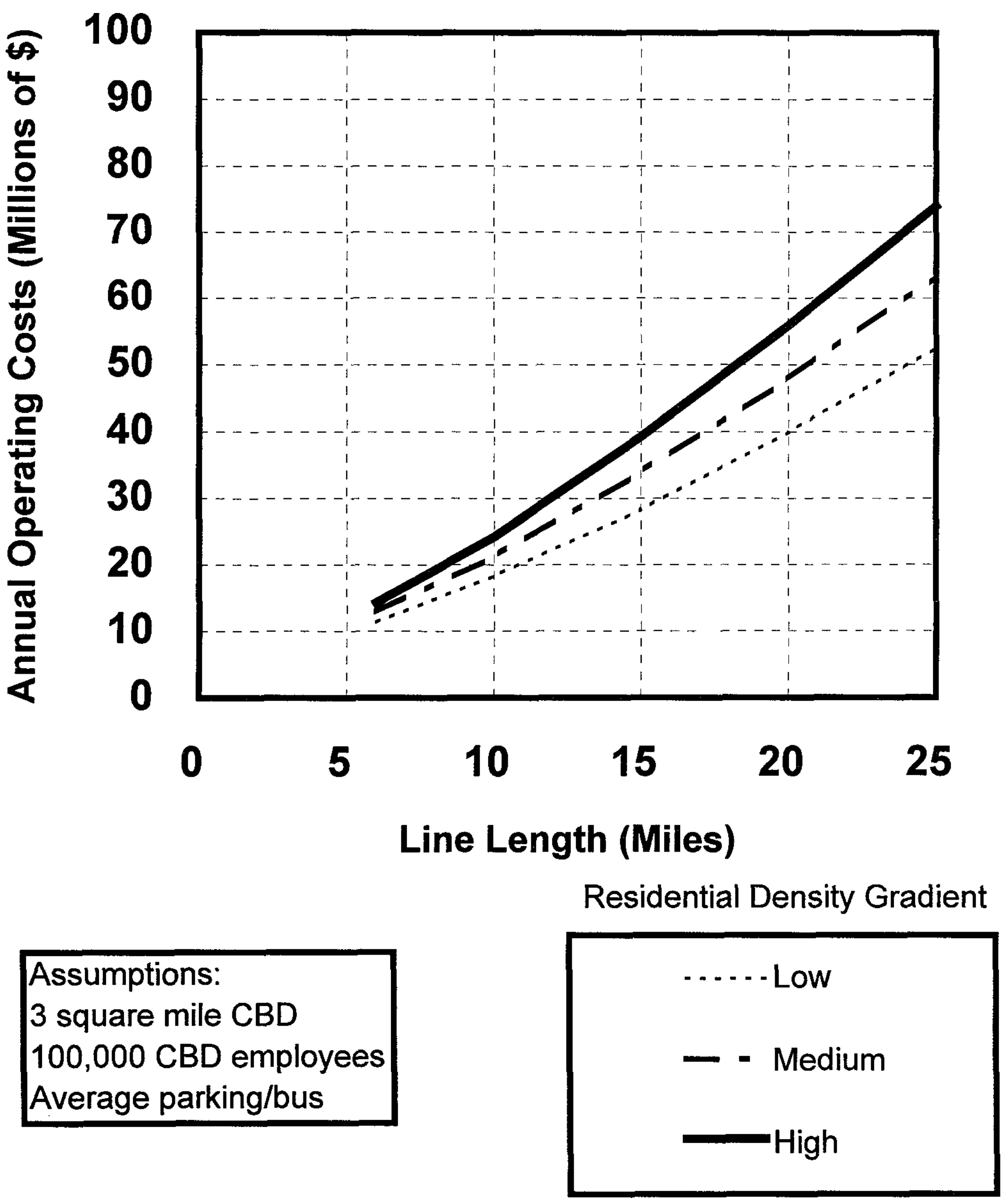


Figure 30.
Light Rail Operating Costs by Line Length and Residential Density Gradient



In Figure 31 the light rail operating costs are shown for different access mode assumptions. Higher operating costs for the scenario with more bus service reflects only the higher cost generated by the higher ridership. The additional operating costs that might result from the provision of more bus service is not accounted for. This was not possible since the variable of bus service was a generic one, and did not quantify a specific amount of feeder bus service. Similarly, any added capital costs for parking beyond that in the cost model is not accounted for. It should be remembered that this analysis focuses on the effects of land use and not access services. Any examination of specific rail lines should, of course, account for site-specific costs associated with access.

Because operating and capital costs track so closely the preceding graphics showed only operating costs. With respect to the variation of employment, employment density, residential density, and access modes, the two cost measures are so similar in shape to make displaying them both here redundant and unnecessary. The absence of capital cost should not be construed to mean that they are less important. Indeed, should there be special capital cost conditions, such as structures or tunnels, or structured parking, the operating and capital cost patterns might diverge substantially.

6.2 COMMUTER RAIL COSTS

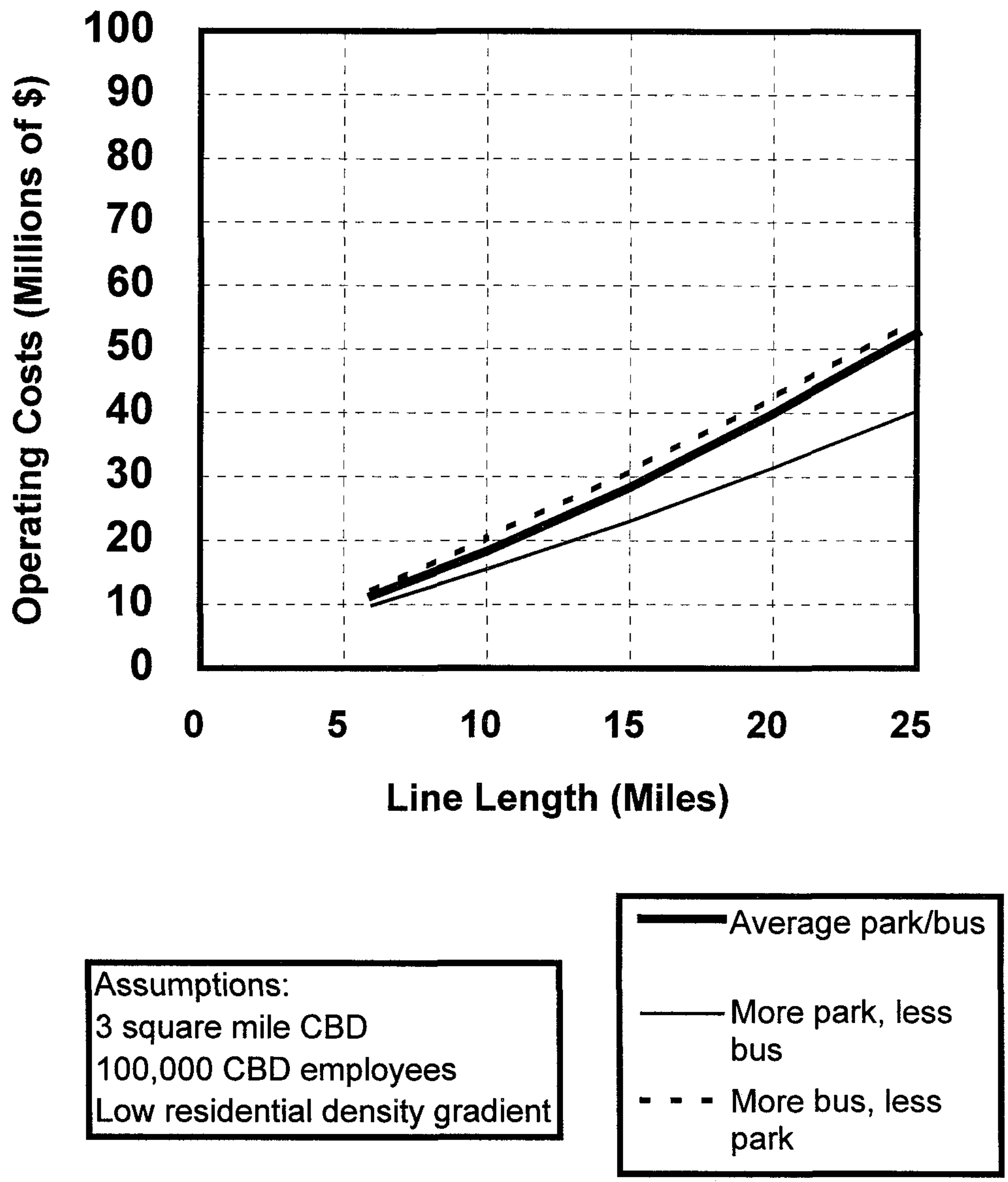
The next series of exhibits displays the annual operating and capital costs for commuter rail. Both sets of curves are shown because operating and capital cost curves for commuter rail, unlike light rail, have different shapes. In the case of commuter rail, the capital costs are more sensitive to line lengths and less sensitive to CBD employment.

This is seen clearly in Figure 32 and Figure 33, showing the variations of costs with CBD employment size and line length. The operating costs increase with both, and particularly where the CBD is large and the line is long. But the capital cost curves are much flatter, with CBD size making little difference, yet the cost of capital jumps with line length.

Because the demand curves for varying residential density gradients showed little variation, the cost curves are not shown for these gradients separately. (The reader can refer back to Figure 15 to find the definitions of residential density gradients used for commuter rail corridors.)

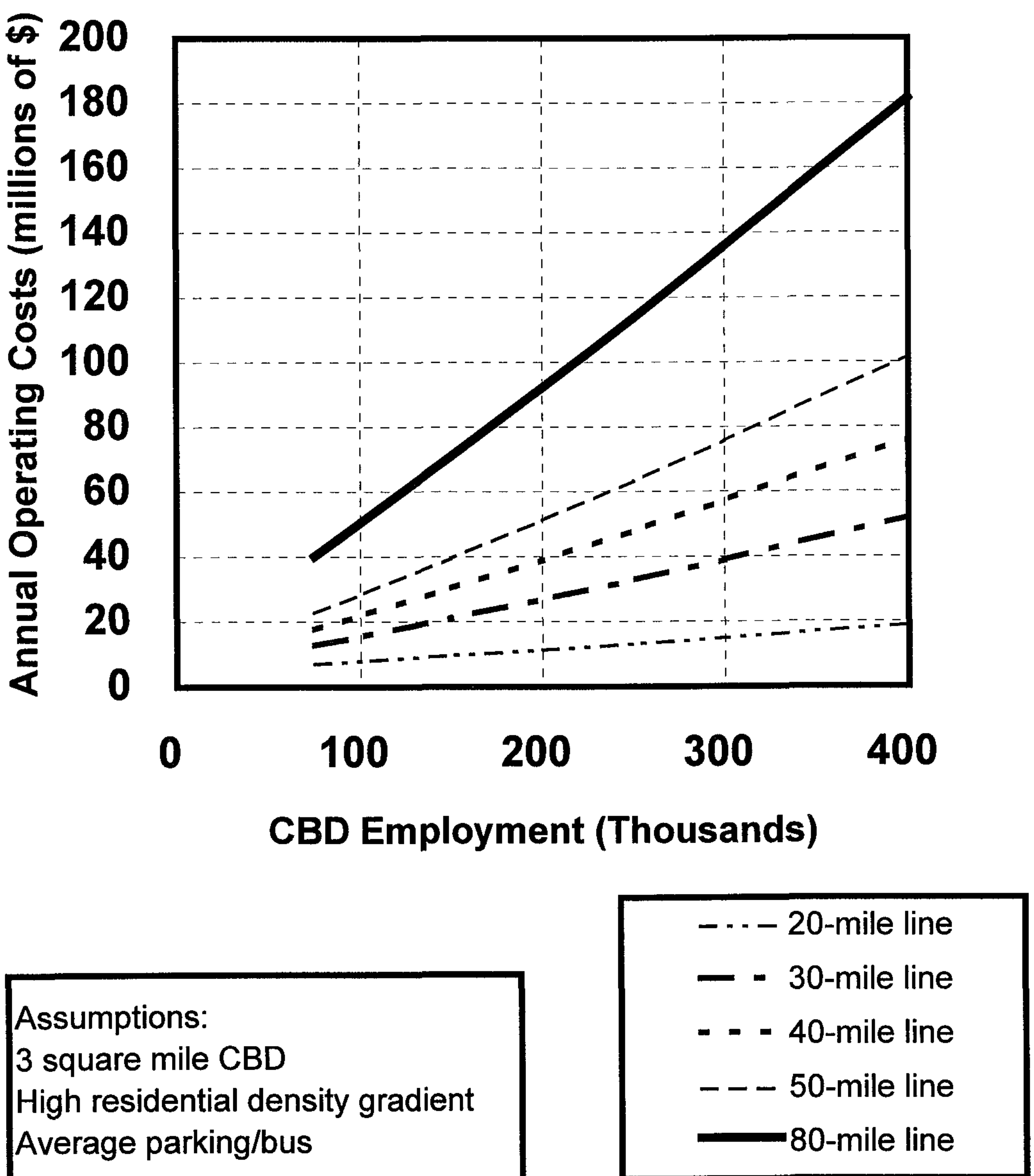
In Figure 34 and Figure 35 the effect of access mode availability is shown. Operating costs here vary much more as different access mode scenarios are tested. This occurs because operating cost is affected strongly by ridership which is a function of access mode, but capital costs are more fixed and independent of the number of riders. This could change if the cost of providing parking is high, such as in structures. Parking costs and feeder bus service costs are accounted for generically in the capital cost model.

Figure 31.
Light Rail Operating Costs by Line Length and Access Modes



Assumptions:
3 square mile CBD
100,000 CBD employees
Low residential density gradient

Figure 32.
Commuter Rail Operating Costs by CBD Jobs and Line Length



Assumptions:
3 square mile CBD
High residential density gradient
Average parking/bus

Figure 33.
Commuter Rail Capital Costs by CBD Jobs and Line Length

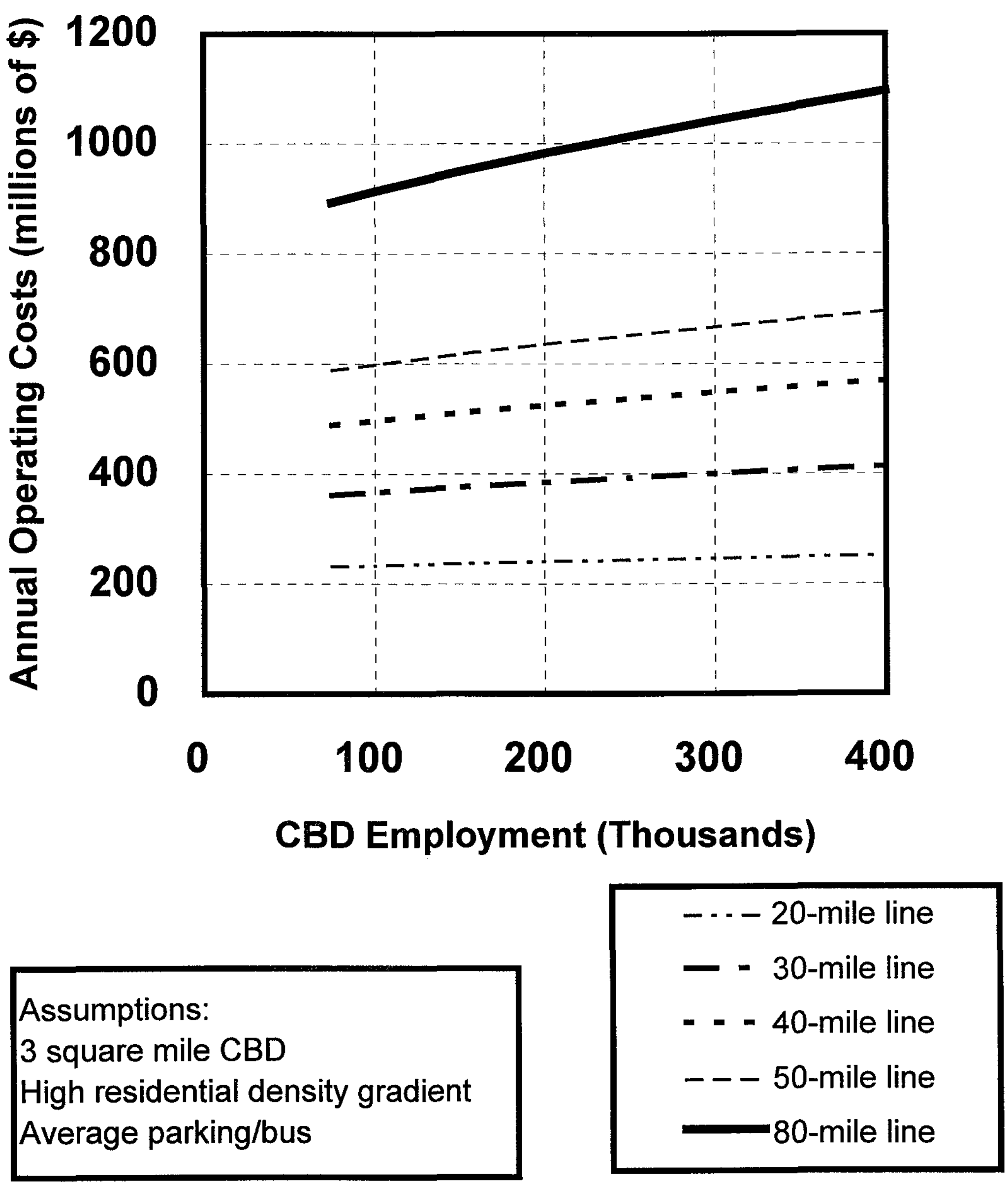


Figure 34.
Commuter Rail Operating Costs by Line Length and Access Modes

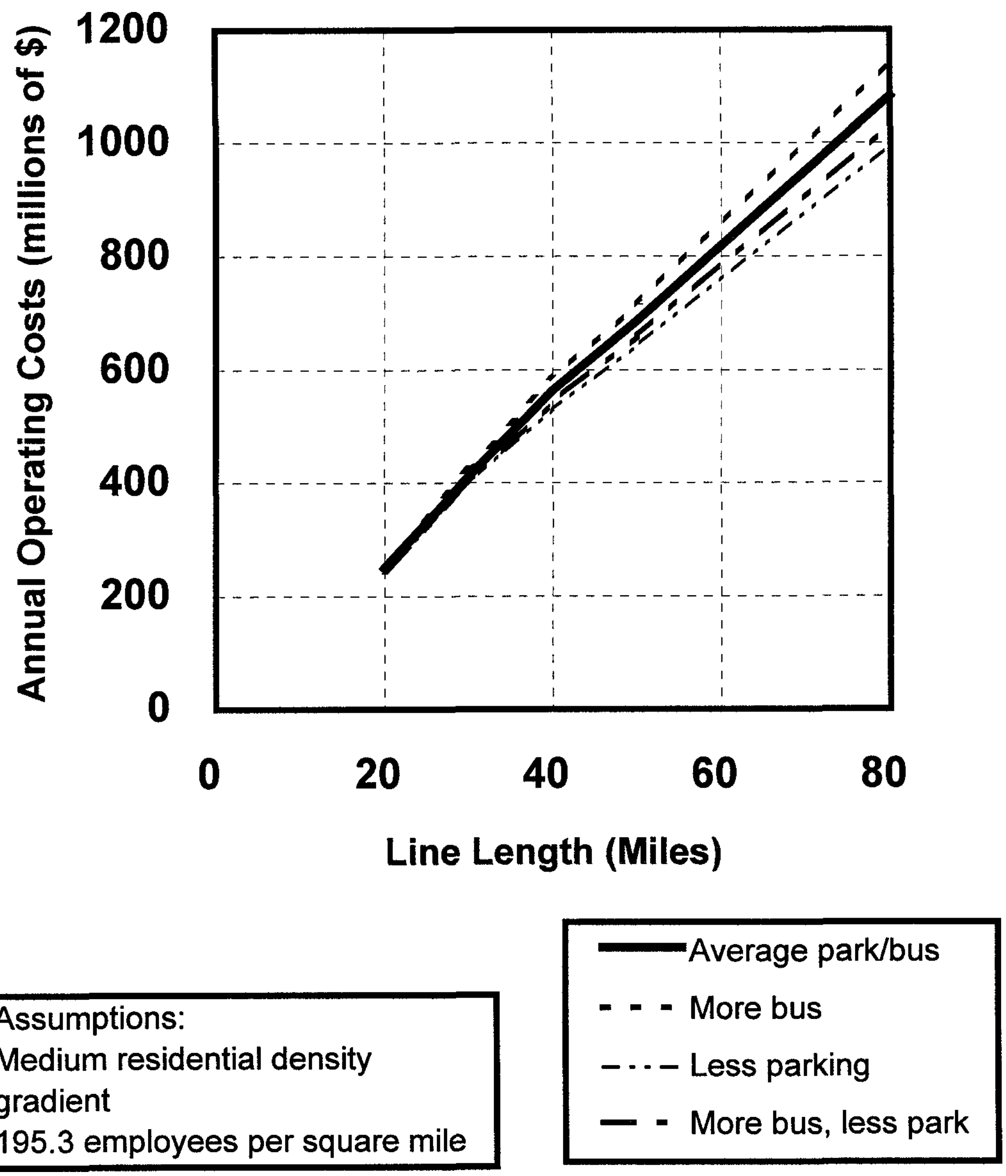
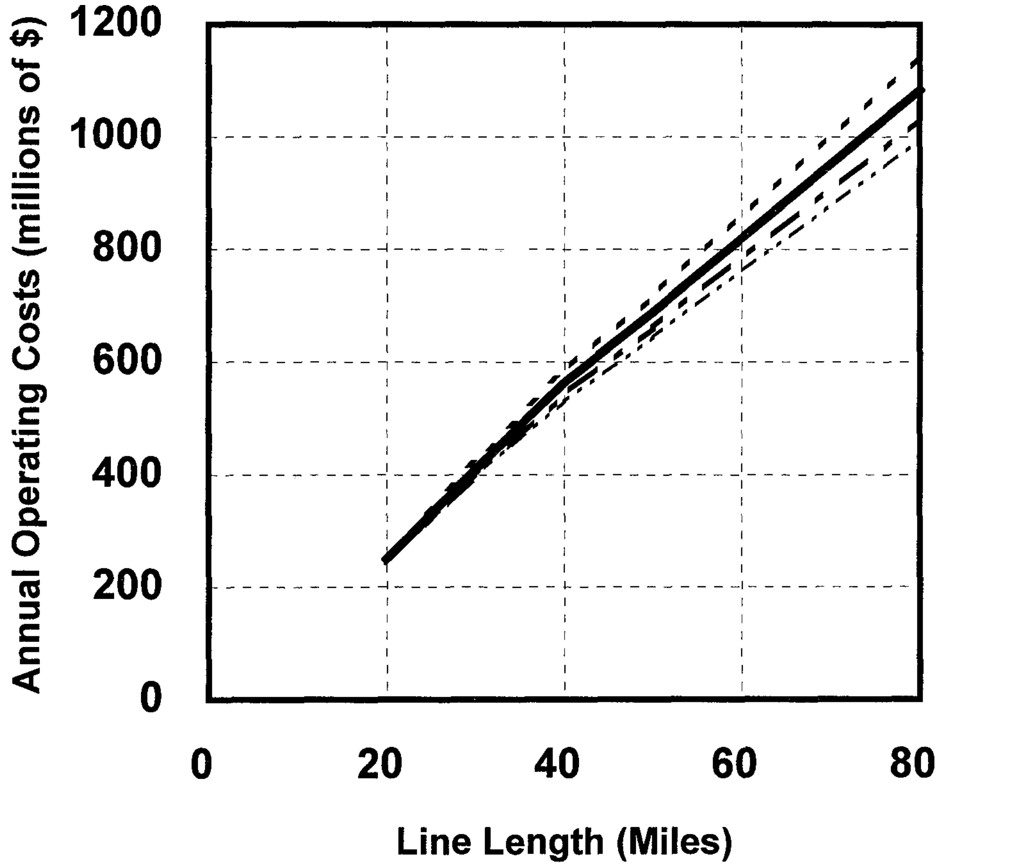


Figure 35.
Commuter Rail Capital Costs by Line Length and Access Modes



Assumptions:
Medium residential density gradient
195.3 employees per square mile

There is certainly value in examining both operating and capital costs separately. They behave differently in many cases with respect to demand. The source of funding for these two costs is usually different, and therefore the decision to build a line and then to provide it with sufficient funds is often made by different parties. Yet, there is also value in combining operating and capital costs in one measure, since once a line is built there must be funds to continue to operate it. Accordingly, one such measure is developed here which adds the annual operating cost to the annual amount that would be needed to ensure the replacement of the capital investment. For this the useful life of the right-of-way and structures is assumed to be 50 years, the stations, 35 years, and the vehicles, 25 years. This cost measure, the annual operating cost including depreciation, will be referred to as the total cost.

6.3 ESTABLISHING THE LIMITS OF RIDERSHIP

Prior to discussing cost-effectiveness, it is helpful to circumscribe them for the levels of ridership for which light rail and commuter rail are either unrealistic or physical impossible. At the extreme, the number of vehicles needed for light rail in the peak, may exceed the frequency possible with today's control systems, even when vehicles are put in trains. If a line can achieve, at best, 90-second headways with three-car trains, or 135 vehicles crossing into the CBD in the peak hour, then it can handle only about 46,000 daily boardings outside the CBD. For demand greater than that higher capacity systems, such as rapid transit (heavy rail) should be considered. Similarly, an upper limit can be reached by commuter rail. Assuming 10-car trains operating every three minutes in the peak, the daily boardings outside the CBD cannot exceed 80,000 persons. However, only in New York are such volumes approached or exceeded.

At the low end of the ridership spectrum, lines attracting too few riders cannot operate effectively. For example, if light rail does not have the ridership to fill vehicles in the peak hour with a frequency of service of eight per hour, or one every 7 1/2 minutes, it may be pointless to operate it because the service is too sparse. Given our assumptions about peaking, 2,700 daily boardings outside the CBD would be the lower ridership threshold, corresponding to one-car trains operating every eight minutes in the peak hour. For commuter rail, a three-car train with three trains per peak hour needs daily boardings outside the CBD of 3,600.

When these limits are applied to the hypothetical corridors, for light rail the high end of the ridership spectrum is exceeded in the following corridors:

- For CBDs with 300,000 jobs, all line lengths;
- For CBDs with 250,000 jobs, all line lengths of 15 miles, for 10-mile lines for all of residential gradients except the highest one coupled with a high density CBD;
- For CBDs with 200,000 jobs, and line lengths of 15 miles, for the higher density gradients and higher CBD densities; and
- For CBDs with 150,000 jobs only at 20 mile lines or more, and then only for the highest residential density gradients.

Collectively, this means that there is a significant range of conditions for large cities where light rail systems are likely to be inappropriate, particularly where CBD jobs are in excess of 250,000. Of course, the fares could be raised to force the light rail line's ridership lower, but that would make it more difficult to complete with the automobile.

On the other hand, the low end light rail threshold of 2,700 boardings does not occur for any of the hypothetical corridors considered. This means, at least on ridership volume grounds, that any region, even with a CBD of only 25,000 jobs, is a possibility for light rail.

None of the hypothetical commuter rail examples had more than the 80,000 daily boardings ceiling. However, the picture for the low end threshold is much different. Daily boardings do not reach the required 3,600 in the following hypothetical corridors:

- For CBDs of 75,000 jobs, all lines of 40 miles or less, and for lines of 50 to 80 miles for the lower CBD employment density (i.e. three square mile CBDs). This means that there are no situations where a CBD of 75,000 and low employment density can support any level of commuter rail service. Where the CBD is more dense (i.e. two square miles), lines of 50 to 80 miles rise above the needed threshold.

- For CBDs of 100,000 jobs, lines of 30 miles in length do not have the ridership to support commuter rail. For lines of 40 miles or more the CBD must be in the higher density category (i.e. two square miles).

- For CBDs of 150,000 jobs, lines of 20 miles can not support commuter rail, and 30-mile lines can only support it if the CBD is dense (i.e. two square miles).

- For CBDs of more than 150,000 jobs, the ridership is sufficient in all cases except if the line is only 20 miles long. In fact, lines of only 20 miles gather enough riders only if the CBD is very large and dense.

- Collectively, the foregoing suggests that commuter rail, at least from a ridership perspective, requires relatively large CBDs and relatively long lines.

6.4 MATCHING RIDERSHIP WITH COSTS

In this section measures of the effectiveness and efficiency of each of the hypothetical corridors are calculated. There are, of course, many measures that can be used. A primary measure of cost-efficiency is the total cost (annual operating cost plus depreciation) divided by the annual-vehicle miles. The numerator encompasses both operating and capital costs. The denominator of this indicator accounts for the amount of service offered as well as the amount of travel that occurs on the line since vehicle-miles were estimated based on passenger-miles. A second measure, passenger-miles per line-mile, measures the effectiveness of the line in carrying its demand. It too was calculated for the hypothetical corridor rail lines.

6.5 LIGHT RAIL EFFECTIVENESS AND EFFICIENCY

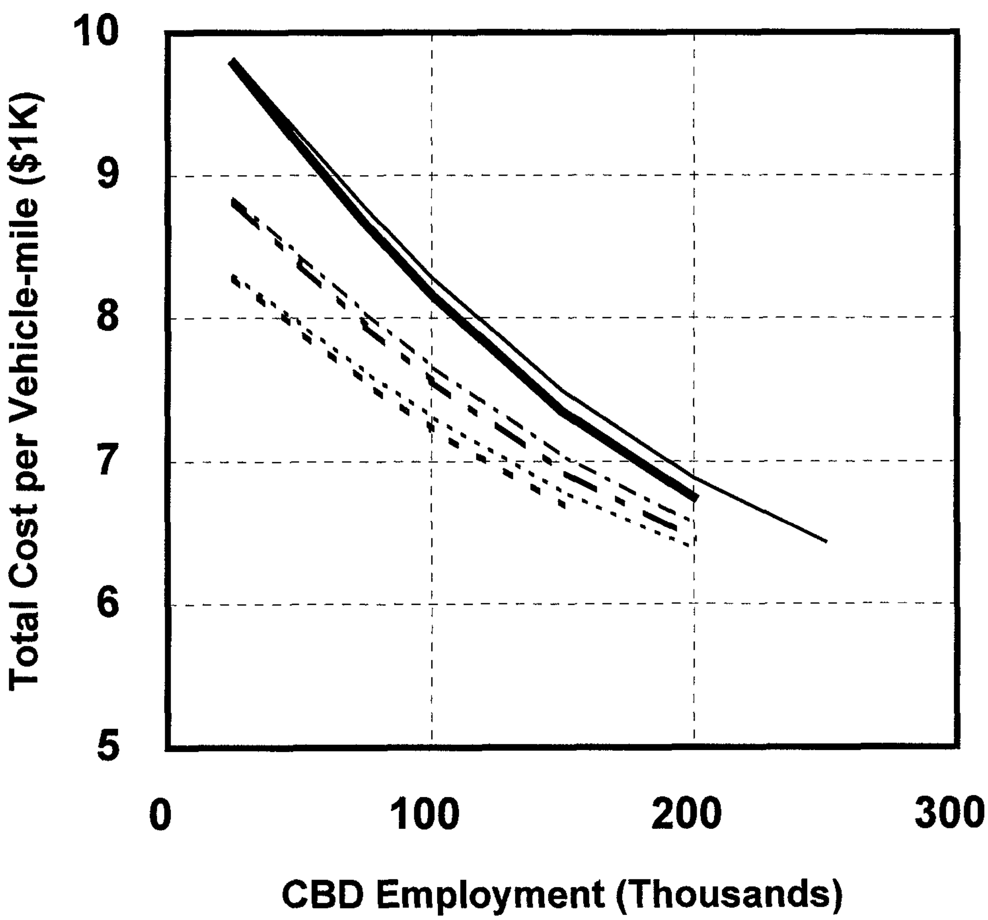
The **total annual cost per vehicle-mile** is plotted against CBD employment and is shown as a family of curves for residential density gradients and employment densities in a series of graphs in Figure 36 through Figure 40. Each exhibit represents a different line length. Each exhibit shows clearly that light rail becomes more cost-efficient with higher CBD employment levels, higher CBD employment densities and higher residential densities, with CBD employment density having the least effect. Many examples can be used to illustrate these points. Typically, the highest residential density gradient performs about 30 cents per vehicle-mile better (from three to five percent better) than the medium residential density gradient, and the medium performs about 50 cents per vehicle-mile better (five to seven percent better) than the low one. Similarly, a CBD of 200,000 jobs performs from 60 cents to $1.20 better (eight to 15 percent better) than a CBD of 100,000 jobs. These curves can also be viewed in trade-off terms. For example, in Figure 37, a high residential density gradient corridor with 150,000 jobs in the CBD, performs about the same as a middle residential corridor with a 200,000 job CBD, and a low residential density corridor with a 250,000 job CBD.

Comparisons among these five figures show that the length of the line also affects the cost-efficiency of a light rail line. Identical density curves among the figures show greater efficiency as the line gets longer, although the benefits get smaller with each increment to the line length.

Passenger-miles per line-mile measures the effectiveness of a line. This is shown in Figure 41 and Figure 42 for 10- and 20-mile light rail lines, respectively. Increases in each of the three land use variables result in a more effective line. Each step up in residential density gradients produces about a 40 percent increase in passenger-miles per line-mile. Increases in CBD employment levels have a progressively greater impact on effectiveness as the levels get higher. For example, for the 10-mile line an increase of CBD jobs from 50,000 to 100,000 for the medium residential density gradient increases passenger-miles per line-mile by about 25 percent, but an increase in CBD jobs from 100,000 to 200,000 creates about a 90 percent increase in effectiveness. The effect of CBD density is smaller but also grows at the high employment levels. Comparison of Figure 41 with Figure 42 show that line length influences effectiveness too, with longer line lengths producing slightly more passenger-miles per line-mile.

Collectively, the measures of cost-efficiency and effectiveness each indicate a strong positive relationship with CBD employment size and residential density. A weaker but significant relationship also occurs for CBD employment density and for line length. This suggests that larger cities with higher density corridors will work best for light rail. But as noted earlier at very high demand levels for larger CBDs, the ridership attracted to light rail may not be practically handled and a higher capacity heavy rail may be called for. At the lower end of the land use spectrum cost-efficiency and effectiveness may suffer, but increases in residential density might make up for smaller CBDs, and conversely more development in the CBD could allow for effective and efficient light rail without any significant increase in residential densities.

Figure 36.
Light Rail Cost-Efficiency by CBD Jobs and Various Densities (6-mile line)

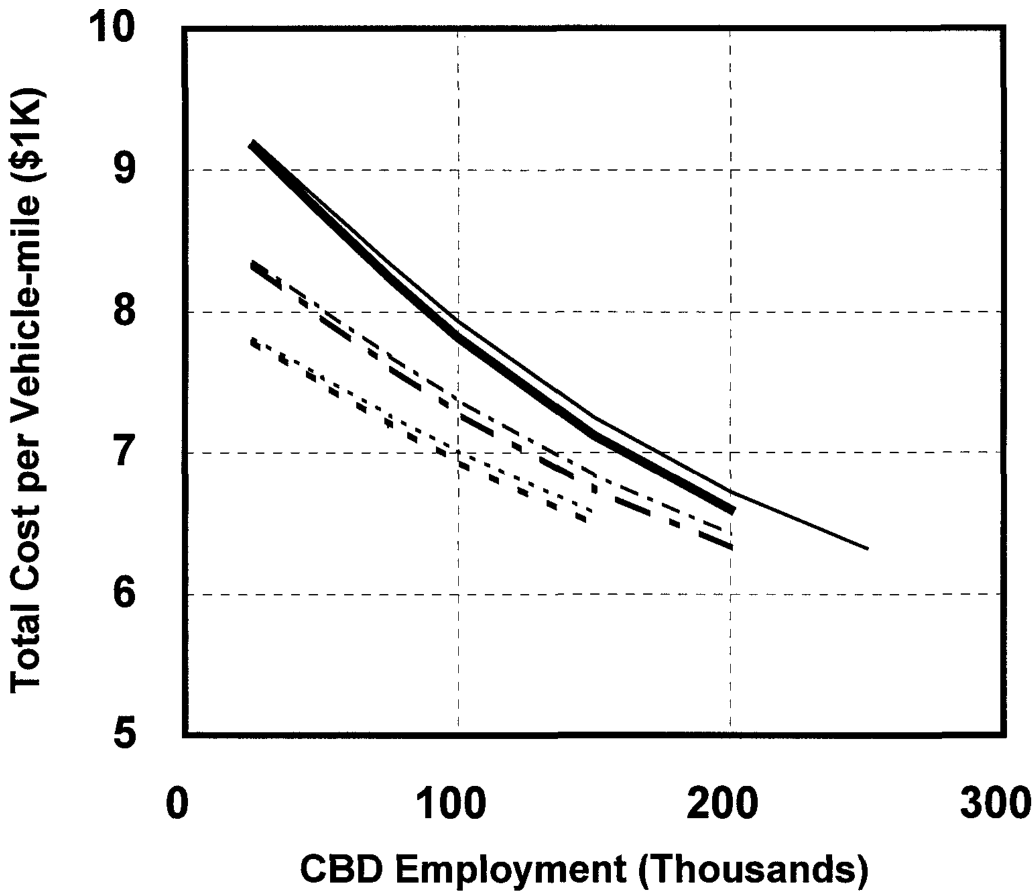


Symbol	Residental Gradient[1]	Employment Density[2]
......	High	Low
- - -	High	High
—·—·	Medium	Low
— -	Medium	High
——	Low	Low
▬▬	Low	High

[1] Residential density varies with distance from the CBD. Figure 14 illustrates the density gradients.

[2] Employment density varies with employment size. A three square mile CBD is low density and a two square mile CBD is high density.

Figure 37.
Light Rail Cost-Efficiency by CBD Jobs and Various Densities (10-mile line)

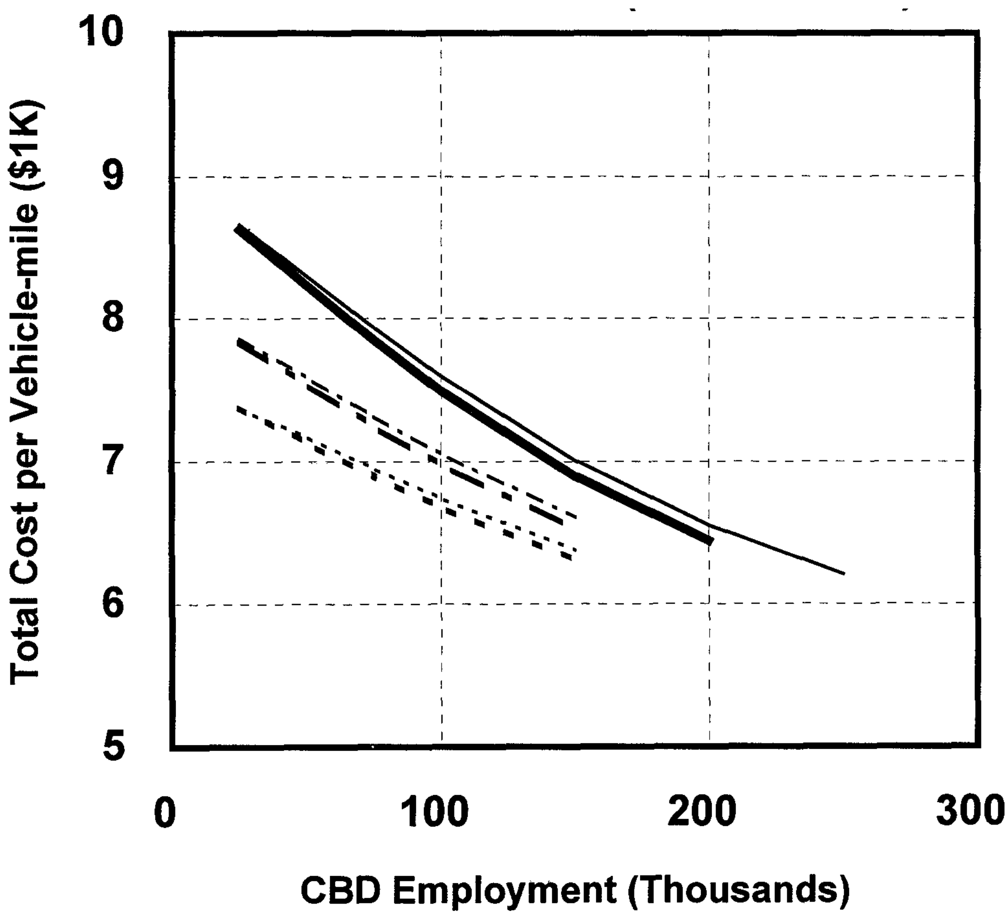


Symbol	Residental Gradient[1]	Employment Density[2]
......	High	Low
- - -	High	High
—·—·	Medium	Low
— -	Medium	High
——	Low	Low
▬▬	Low	High

[1] Residential density varies with distance from the CBD. Figure 14 illustrates the density gradients.

[2] Employment density varies with employment size. A three square mile CBD is low density and a two square mile CBD is high density.

Figure 38.
Light Rail Cost-Efficiency by CBD Jobs and Various Densities (15-mile line)

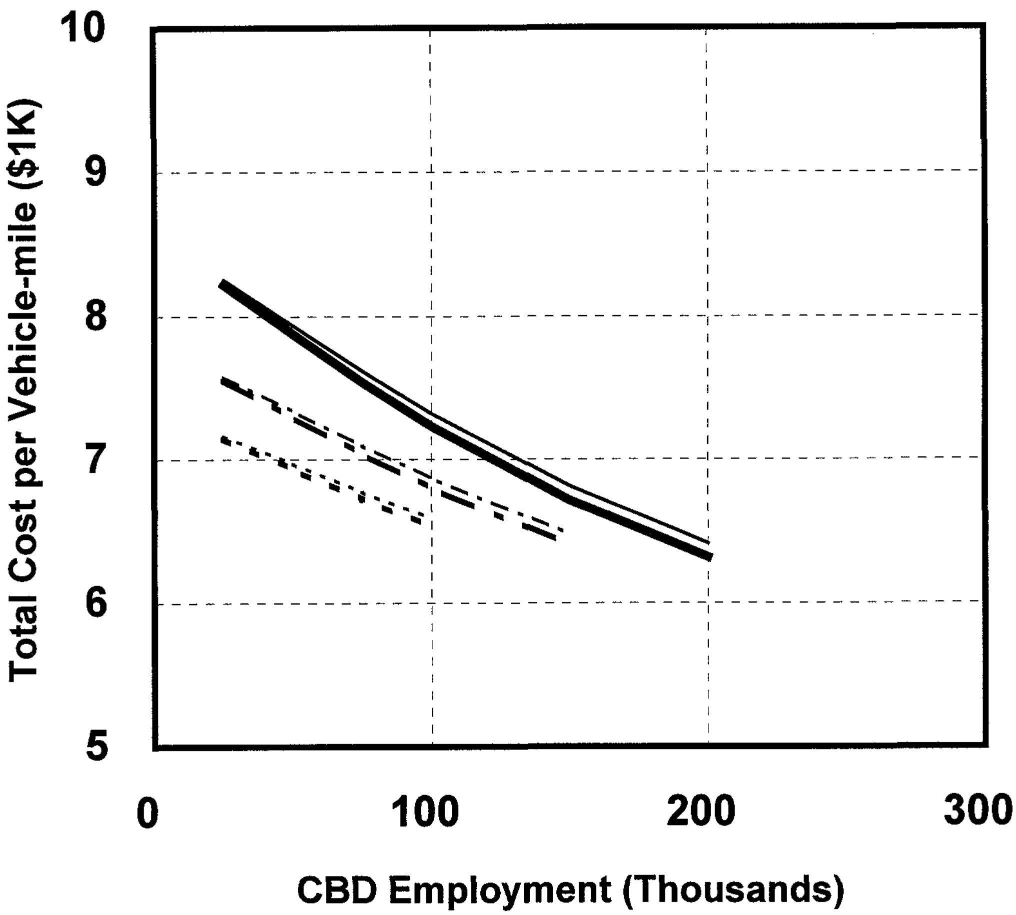


Symbol	Residental Gradient[1]	Employment Density[2]
......	High	Low
- - -	High	High
—·—·	Medium	Low
— -	Medium	High
—— (thin)	Low	Low
—— (thick)	Low	High

[1] Residential density varies with distance from the CBD. Figure 14 illustrates the density gradients.

[2] Employment density varies with employment size. A three square mile CBD is low density and a two square mile CBD is high density.

Figure 39.
Light Rail Cost-Efficiency by CBD Jobs and Various Densities (20-mile line)

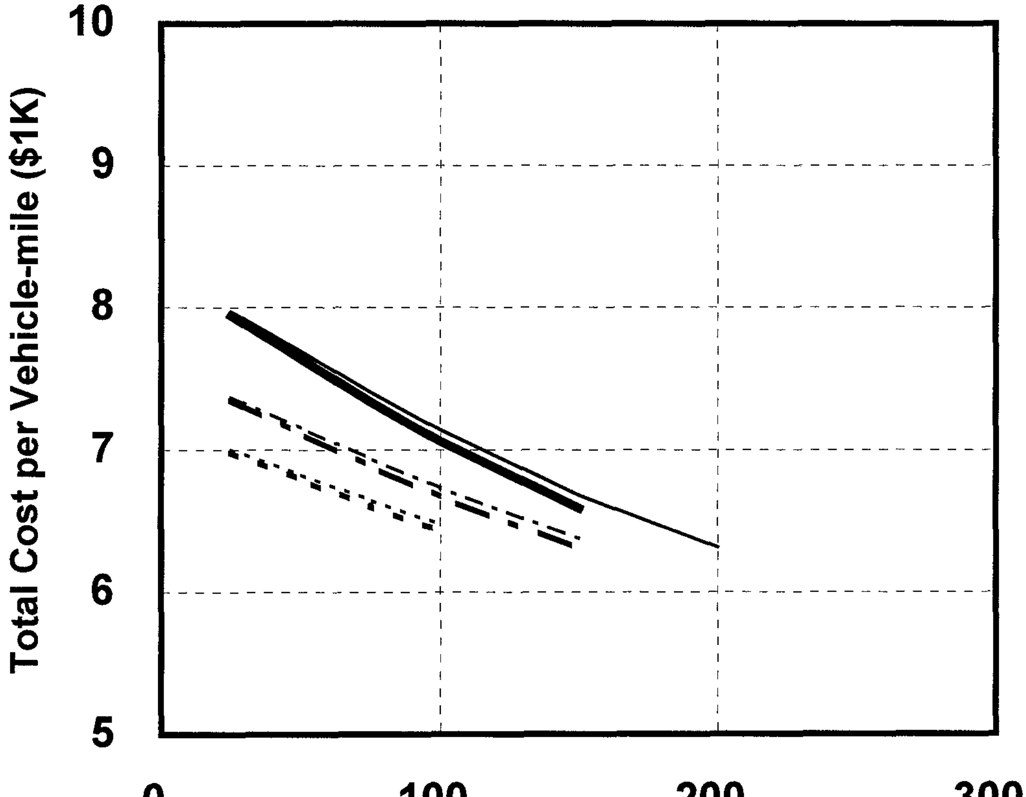


Symbol	Residental Gradient[1]	Employment Density[2]
- - - - - -	High	Low
▪ ▪ ▪	High	High
— · — ·	Medium	Low
— ▪	Medium	High
———	Low	Low
━━━	Low	High

[1] Residential density varies with distance from the CBD. Figure 14 illustrates the density gradients.

[2] Employment density varies with employment size. A three square mile CBD is low density and a two square mile CBD is high density.

Figure 40.
Light Rail Cost-Efficiency by CBD Jobs and Various Densities (25-mile line)

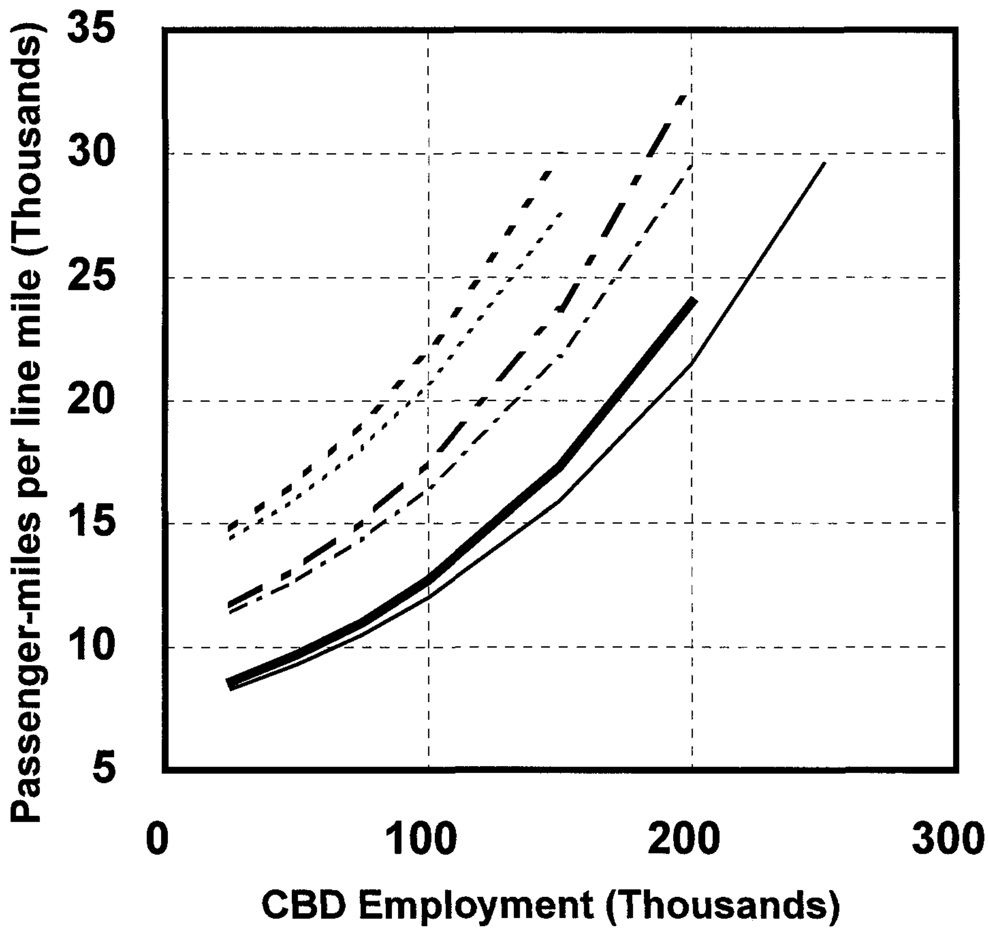


Symbol	Residental Gradient[1]	Employment Density[2]
- - - - - -	High	Low
▪ ▪ ▪	High	High
— · — ·	Medium	Low
▬ ▪	Medium	High
——	Low	Low
▬▬	Low	High

[1] Residential density varies with distance from the CBD. Figure 14 illustrates the density gradients.

[2] Employment density varies with employment size. A three square mile CBD is low density and a two square mile CBD is high density.

Figure 41.
Light Rail Effectiveness by CBD Jobs and Various Densities (10-mile line)

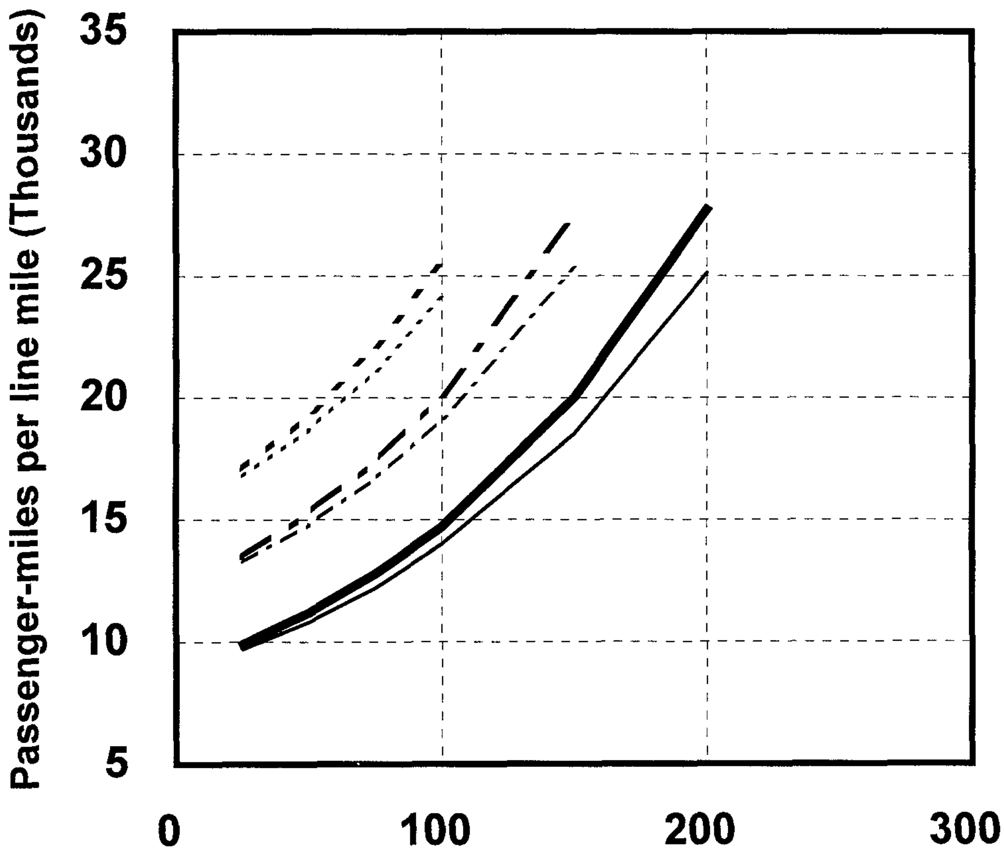


Symbol	Residental Gradient[1]	Employment Density[2]
......	High	Low
- - -	High	High
—·—·	Medium	Low
— -	Medium	High
—— (thin)	Low	Low
—— (thick)	Low	High

[1] Residential density varies with distance from the CBD. Figure 14 illustrates the density gradients.

[2] Employment density varies with employment size. A three square mile CBD is low density and a two square mile CBD is high density.

Figure 42.
Light Rail Effectiveness by CBD Jobs and Various Densities (20-mile line)



Symbol	Residental Gradient[1]	Employment Density[2]
......	High	Low
- - -	High	High
—·—·	Medium	Low
— -	Medium	High
——	Low	Low
▬▬	Low	High

[1] Residential density varies with distance from the CBD. Figure 14 illustrates the density gradients.

[2] Employment density varies with employment size. A three square mile CBD is low density and a two square mile CBD is high density.

Recall that ridership gains can be realized on light rail lines with more feeder bus service and, to a lesser extent with more parking at stations. The availability of these access modes beyond the levels implicit in the ridership model could allow for higher performance levels without the need to increase either residential density gradients or CBD employment levels.

6.6 COMMUTER RAIL EFFECTIVENESS AND EFFICIENCY

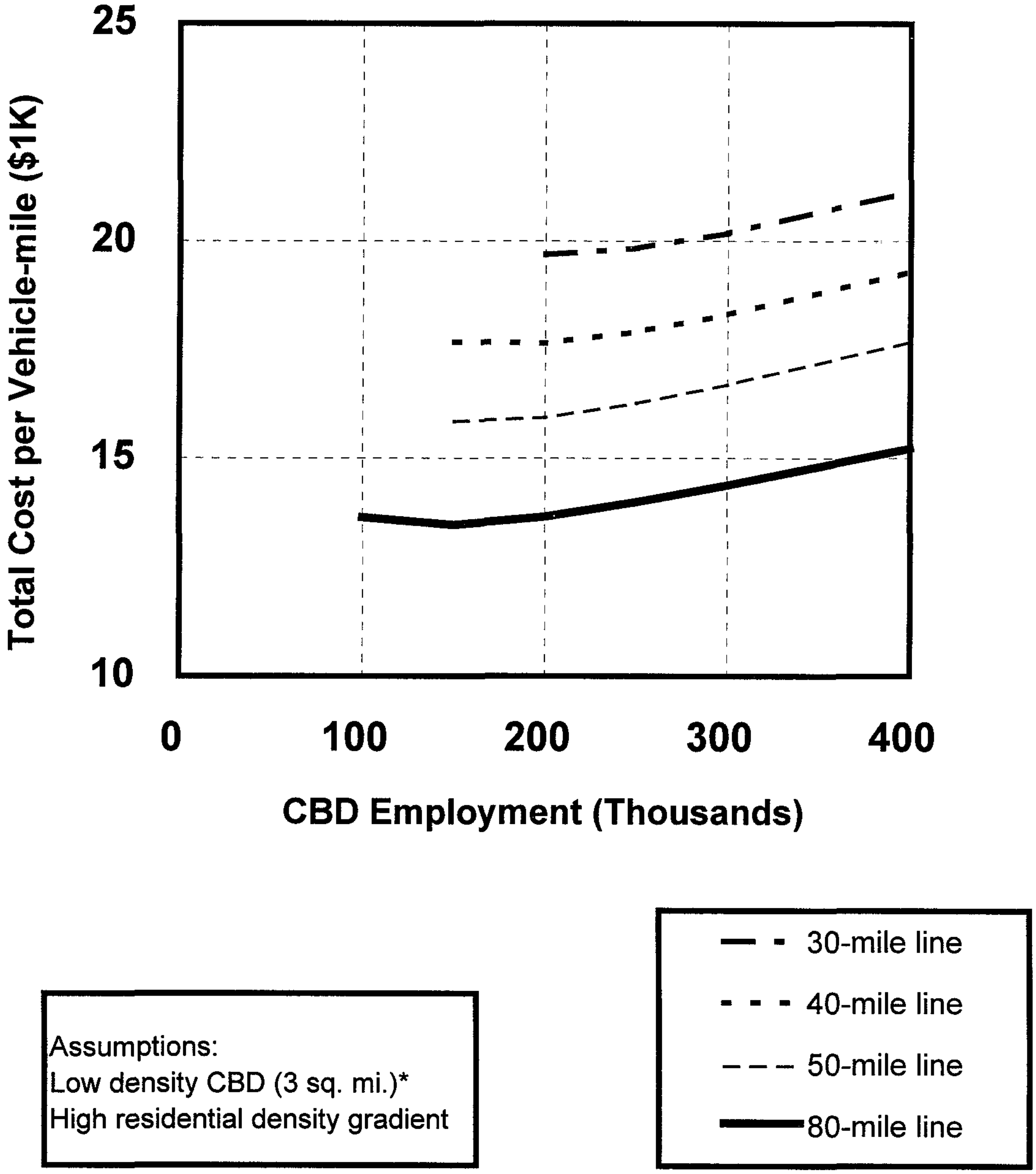
As was done for the hypothetical light rail lines, the total cost per annual vehicle-mile, a measure of cost-efficiency, was calculated. The intent is to show the variation of this important measure as a function of land use characteristics. As will be recalled for commuter rail the residential density gradients had little effect on ridership. Not surprising then, the variation of total cost per annual vehicle-mile shows little variation from one residential density to another. Consequently, rather than plotting the total cost per annual vehicle-mile for each of the residential density gradients, one series of plots varying CBD employment and CBD size was done. This makes it possible to effectively show each of the line lengths on two graphs, as depicted in Figure 43 and Figure 44.

The variation in the total cost per annual vehicle-mile indicator is more pronounced by line length than by CBD employment. Each successively higher line length costs about $2.00 less per vehicle mile (ten to 15 percent). Meanwhile, variations in CBD employment increase costs by about $1.00 per vehicle-mile (five to seven percent) over its entire range. (Note that some of the lines do not extend to the lowest CBD employment sizes since the ridership will be insufficient to sustain a minimal service, as discussed earlier.) However, CBD size and, therefore, employment density do have a strong effect. Not only do the higher density CBDs imply higher costs per vehicle-mile but their curves are steeper, moving upward about $3.00 over the range of CBD employment levels. In sum, the cost-efficiency indicator suggests that from the perspective of cost per vehicle-mile the more cost-efficient commuter rail lines are the longer ones, and that this is true over the full range of CBD employment, although higher density CBDs are somewhat less cost-effective.

To examine this matter further, the effectiveness measure, passenger-miles per line-mile was also calculated and plotted. In Figure 45 and Figure 46 this measure is shown versus CBD employment size for high and low CBD employment densities and by line length. The picture is significantly different than the one in Figure 43 and Figure 44. Employment size and density both matter a lot. CBDs of 400,000 jobs carry almost twice the passenger-miles per line-mile as CBDs of 200,000. Higher CBD density adds about 1,000 passenger-miles per line-mile. The effect of line length is less evident. The 50-mile line is more effective than either the longer or shorter lines.

As with light rail, ridership gains on commuter rail can be realized with more access services, particularly more parking at commuter rail stations, making the commuter rail lines perform better.

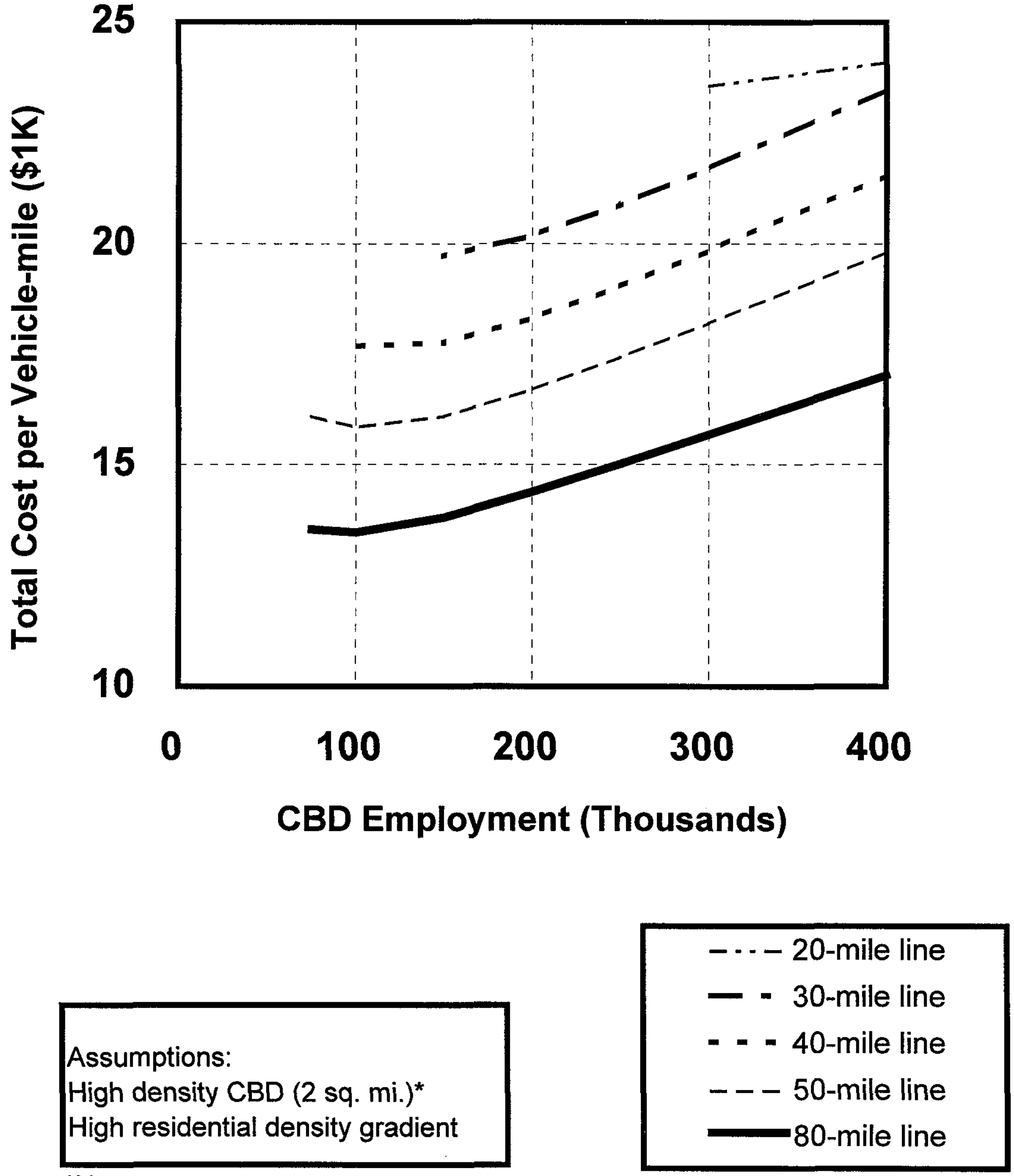
Figure 43.
Commuter Rail Cost-Efficiency by CBD Employment and Line Length (Low Employment Density)



Assumptions:
Low density CBD (3 sq. mi.)*
High residential density gradient

*Note:
CBD density varies with CBD employment size.

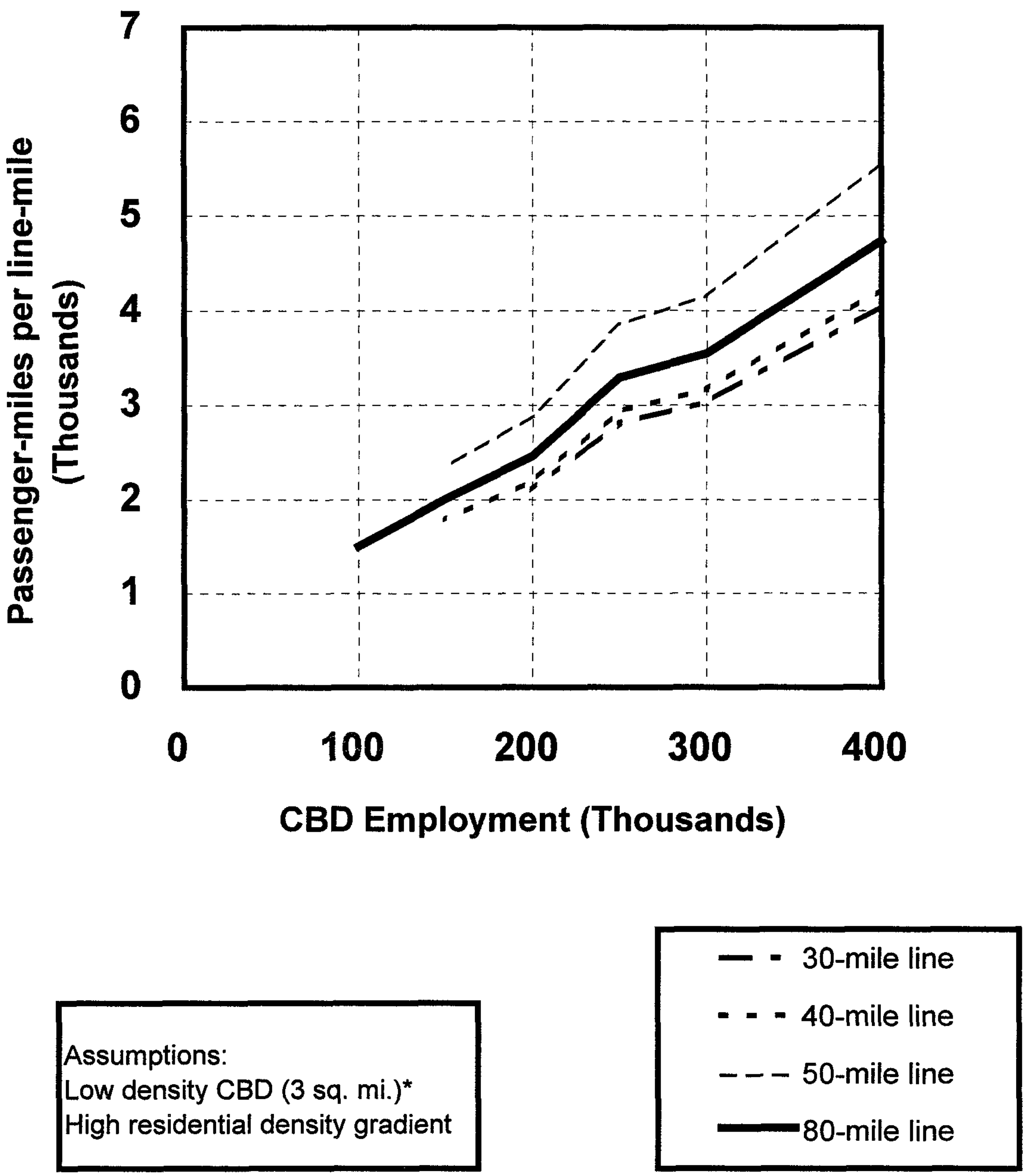
Figure 44.
Commuter Rail Cost-Efficiency by CBD Employment and Line Length (High Employment Density)



Assumptions:
High density CBD (2 sq. mi.)*
High residential density gradient

*Note:
CBD density varies with CBD employment size.

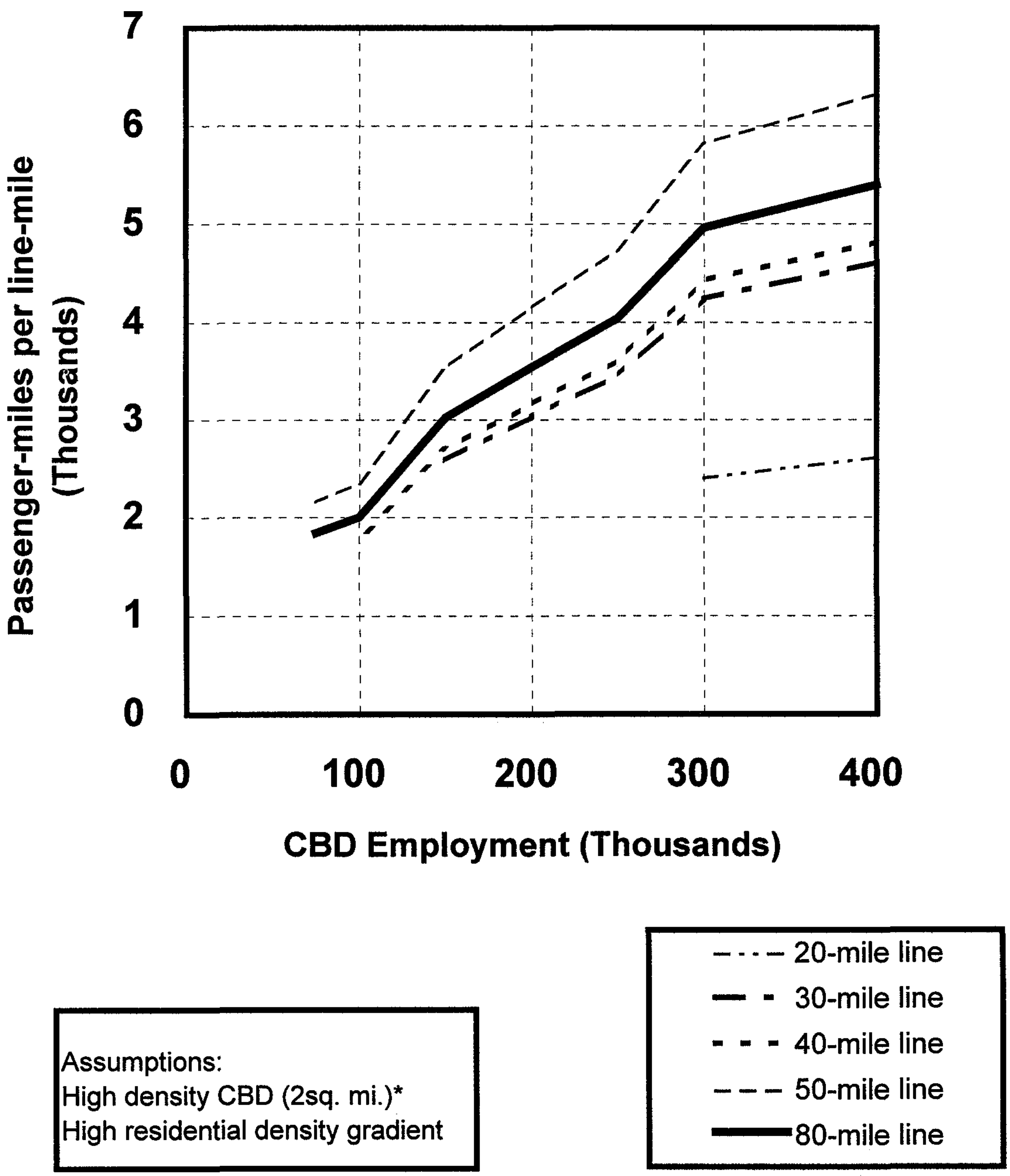
Figure 45.
Commuter Rail Effectiveness by CBD Employment and Line Length (Low Employment Density)



Assumptions:
Low density CBD (3 sq. mi.)*
High residential density gradient

*Note:
CBD density varies with CBD employment size.

Figure 46.
Commuter Rail Effectiveness by CBD Employment and Line Length (High Employment Density)



Assumptions:
High density CBD (2sq. mi.)*
High residential density gradient

*Note:
CBD density varies with CBD employment size.

In sum, within the range of feasible commuter rail corridors much more travel will be accommodated on lines to larger and more dense CBDs. But there is a cost-efficiency trade-off. The larger and more dense CBDs will cost more on a per vehicle-mile basis. That can be mitigated by making the line longer. But that too involves a trade-off, since longer lines will cost more to construct.

7.0 CONCLUSIONS

The analysis described in this report, summarized in Table 16, suggests strongly that light rail and commuter rail transit performs better when there is a large Central Business District. In fact, light rail may not work at all when CBDs get too large since ridership may outstrip the mode's carrying capacity. For commuter rail, the larger CBDs produce more effective services, but are slightly less cost-efficient.

The density of the CBD is particularly important for commuter rail, probably because there is usually only one terminal station and lower density CBDs may put some jobs beyond easy reach of the terminal station. Light rail, in contrast, is less affected by the density of the CBD since there are likely to be multiple stations to serve lower density CBDs.

The importance of both the size and density of Central Business Districts suggest that corridors that do not pass through or terminate in a Central Business District would be harder pressed to be cost-effective.

Residential density itself matters for light rail and commuter rail but, in the latter case, density is confounded by the effect of income, since commuter rail's higher fares attracts more riders with higher incomes, who also tend to live at lower densities.

The length of the rail line assumes some importance for both light rail and for commuter rail. Longer light rail lines are both slightly more cost-efficient and effective. But the effects diminish with length. Commuter rail lines are much more cost-efficient when they are longer and their effectiveness declines beyond 50 miles. At short distances there often is not enough riders to justify even minimal service.

The availability of parking and feeder bus service can help to achieve higher performance levels, all else being equal; feeder buses more strongly affect light rail and parking more strongly affects commuter rail.

Among the more interesting findings in this research is the distinctly different characteristics of light rail and commuter rail. It is clear that they serve different markets and different land uses patterns. Indeed, there are more dissimilarities than similarities. This does not imply that in any one metropolitan area they both may not have a niche, only that they have different niches.

Not accounted for here but worthy of serious exploration is a fuller consideration of costs, including those saved as a result of other modes not used, if the rail line is put in place. To accomplish this is it would desirable to assign the rail ridership to the modes from which riders would be diverted — auto and bus — and estimate the appropriate savings in operating, capital and full environmental costs. Beyond that, the application of the full costs of both transit and highway modes can balance the burden that rail transit must now bear in proving its value.

Finally, this effort should not be viewed as a substitute for a careful examination of all transportation alternatives in all types of corridors including those that do not end in a CBD, accounting for site-specific conditions and preferences. Rather, it should be seen as a means to understand the role that land uses in a corridor play in determining costs.

Further, it makes clear the need to integrate transit planning with land use planning at the earliest possible stage, a finding that is reinforced in the case studies prepared for another report of this project, Public Policy and Transit Oriented Development: Six International Case Studies.

Table 16. Summary of Findings on Cost Efficiency and Effectiveness for Hypothetical Rail Corridors

Factor	Cost Efficiency	Effectiveness
Light Rail		
Residential density gradient	highly positive	highly positive
CBD employment	moderately negative at high CBD job levels may not be possible	highly positive
CBD employment density	slightly positive	moderately positive greater impact for larger CBDs
Feeder bus	unclear	highly positive
Parking availability	unclear (site-specific)	moderately positive
Line length	slightly positive	slightly positive
Commuter Rail		
Residential density gradient	not significant	not significant
CBD employment	slightly negative, for smaller CBDs may have insufficient riders, especially for shorter line lengths	highly positive
CBD employment density	highly positive	highly positive
Feeder bus	unclear	moderately positive
Parking availability	unclear (site-specific)	highly positive
Line length	strongly positive, insufficient riders for shorter lengths	varies, best at 50-mile length

APPENDIX A

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Ridership Models for the Bay Area Rapid Transit System: Influences of Built Environment and Other Factors on Station Passenger Trips

1.0 Introduction

This analysis complements the main analysis of Topic 1 by conducting a in-depth analysis of how the land-use environment shapes transit demand for a single transit system — the Bay Area Rapid Transit (BART). While other modeling conducted under Topic 1 has concentrated on studying light rail and commuter rail services, this analysis is carried out for a heavy rail system. Along with the Chicago metropolitan area, the San Francisco Bay Area is being used as a case context for conducting fairly in-depth analyses for most topics of the Phase II study. This modeling also includes detailed information that could not be included in the United States model because it was not available for all systems. This includes information about the type and mix of land uses near stations and employment densities near all stations, not just in the central business district.

In estimating demand models, stations represent individual cases. The BART system presently has 34 stations (see Figure 1), so there are 34 data points used in the analysis. Ridership data compiled from the Spring of 1990, representing turnstile entries and exits, serve as the main dependent variable for the analyses. Besides station-by-station ridership totals, analyses are also conducted for ridership rates — specifically, ridership per 1,000 population in the catchment area, and ridership per square mile of the catchment area. Each of the 34 BART stations has a catchment area, and these are identified in the Topic 3 report. A catchment area is a contiguous area that captured 90 percent of all access trips to and egress trips from a BART station. The average catchment area is around 90 square miles with a radius of around 7 miles, though as noted in the Topic 3 report, there is considerable variation around these averages. In general, findings of *ridership rates* (e.g., trips per 1,000 population of the catchment area) are likely to be most useful from a policy-making standpoint since such statistics are more easily transferable to other transit properties.

2.0 Research Methods

Multiple regression was used for modeling the influence of various land-use, pricing, service, and other factors on the demand for BART trips. Both linear and log-log functional forms were estimated and are presented. The overall fits of both function forms were fairly good. One advantage of presenting log-log models is that regression coefficients represent elasticities. Thus the relative sensitivity of transit demand to land-use variables, price, service levels, and other factors can be easily compared using elasticities. Elasticities are generally well-understood by practitioners, and can be directly applied to ridership models developed by local transit properties.

In addition, graphs that reveal the sensitivity of transit trips to land-use variables and other control factors are presented in this report. These graphs are generally more intuitive and accessible than the regression results.

The process of developing regression models involved a fairly data intensive effort. Initially, associative relationships between variables were postulated (as discussed below). This was followed by generating various correlation matrices and scatterplots among variables. Attempts were made to estimate fully specified models that incorporated many of the variables that classical economic theories suggest influence travel demand. Because of multi-collinearity among many of the candidate variables and in an effort to present reasonably intuitive and parsimonious models, variables were selected that, in combination, provided a good predictive model that met underlying assumptions of ordinary least squares estimation. Various residual diagnostics were also employed in estimating models.

2.1 Variables Used in Analysis

Three dependent variables, listed and defined in Table 1, were used in the analysis. Models estimating total weekday passenger trips are, by design, scaled to the unique ridership characteristics of the BART system. Thus, the two rate measures of ridership demand — passenger trips per 1,000 population and passenger trips per square mile — were estimated, using the defined catchment area of each station as the geographic region for gauging population and land area.

Five sets of predictor variables were used: land use, pricing, bus service, transportation supply, and demographic. These sets and the variable in each set are also listed and defined in Table 1.

Land Use Variables

The land use variables are the ones of primary policy focus of this report. Employment and population density are the principle land-use variables examined in this study. Employment density was measured as employees per acre for a one mile radius from downtown stations and two mile radius around all other stations. A fairly restrictive geographic area was chosen for measuring employment density (as opposed to catchment areas) because of the nature of access trips to and egress trips from work sites. Since at the work end of trips most employees do not have access to cars, trips tend to be short. Thus, as discussed in the Topic 3 report, limiting the analysis of employment densities to the area reasonably close to rail stations is appropriate. Population density, however, is expressed for the entire catchment area — specifically,

Table 1. Dependent and Candidate Independent Variables Used for Modeling Transit Demand for the BART System

Dependent Variables

ENTRIES Average weekday entries through station turnstiles, Spring 1990. See Appendix B. Source: BART Planning Department.

EXITS Average weekday exits through station turnstiles, Spring 1990. See Appendix X. Source: BART Planning Department.

RIDERS Total weekday passenger trips entering and exiting station, Spring 1990. ENTRIES EXITS

RIDEPOP Weekday passenger trips (entries and exits) at station per 1,000 population in station catchment area. Catchment area is contiguous area that captures 90% of all access trips to and egress trips from station.

RIDEAREA Weekday passenger trips (entries and exits) at station per square mile of station catchment area.

Land Use Variables

EMPDENS Employment density, in employees per acre in 1990. Measured for census tracts and block groups that encompass a one mile radius around downtown stations (Embarcadero, Montgomery, Powell, Civic Center, Oakland 12th St., Oakland 19th St., and Berkeley) and a two mile radius around other stations. GIS used to create buffers for estimating employment within these radii. Source: 1990 Census Transportation Planning Package, Part II, Metropolitan Transportation Commission.

POPDENS Population density, in 1990 population per square mile of station catchment area. Source: 1990 census, STF-3A.

AREA Area of catchment zone, in square miles. GIS used for computing area.

ENTROPY Index of land-use mixture. Entropy = $\{;_i[p_i{}^{*}\ln(p_i)]\}/\ln(k)$ where p_i = proportion of land area in land-use category i, and k = number of land-use categories; ranges between 0 and 1, where 0 signifies land devoted to a single use and 1 signifies all land area is evenly spread among all uses.

COMMERCI, INDUSTRI, RESIDENT Proportion of land area in commercial use for one-mile radius around station. Source: 1990. Association of Bay Area Governments land use inventory.

Table 1 (Continued). Dependent and Candidate Independent Variables Used for Modeling Transit Demand for the BART System

Pricing Variables

AVGFARE Average oneway adult cash fare from each station to all other stations, Spring 1990. Calculated from BART fare matrix. Source: BART Planning Department.

CBDFARE Oneway adult cash fare from station to the downtown San Francisco Montgomery Street Station, Spring 1990.

Complementary and Competing Bus Service Variables

FEEDER Route miles of all bus services in station catchment area that feed into BART station (i.e., bus stop is within 200 feet of station entrance). These are complementary services. Bus services include AC Transit, San Francisco Muni (diesel and electric trolley), Golden Gate Transit, SamTrans, Central Contra Costa County Transit, and municipally sponsored shuttle services. (Light rail and cable car feeder mile in San Francisco is not included.) Data files were obtained from the Metropolitan Transportation Commission containing geocoded points for bus stops; route mile distances were calculated by overlaying a street layer on the bus route layer and using GIS distance measuring functions. Source: Data files provided by the Metropolitan Transportation Commission and local transit agencies.

PARALLEL Route miles of all bus services in station catchment area that do not fee into BART station and that essentially parallel BART lines within the catchment zone. These are competitive services. Bus services include AC Transit, San Francisco Muni (diesel and electric trolley), Golden Gate Transit, SamTrans, Central Contra Costa County Transit, and municipally sponsored shuttle services. (Light rail and cable car feeder mile in San Francisco is not included.) Data files were obtained from the Metropolitan Transportation Commission containing geocoded points for bus stops; route mile distances were calculated by overlaying a street layer on the bus route layer and using GIS distance measuring functions. Source: Data files provided by the Metropolitan Transportation Commission and local transit agencies.

Table 1 (Continued). Dependent and Candidate Independent Variables Used for Modeling Transit Demand for the BART System

Transportation Supply Variables

PARKING	Park-and-ride spaces at station, surface and structured. Source: BART *Systemwide Parking Inventory, 1990.*
TERM_NT	Terminal or Near-Terminal Station (0 = no, 1 = yes). Near-terminal stations are those toward the end of a line that function like terminals because they are closer to freeways than actual terminals and thus serve a larger catchment area. BART's near terminal stations, El Cerrito del Norte and Pleasant Hill, have larger supplies of parking than terminal stations since they are easier to reach by freeway.
FWYPX	Freeway proximity. Lineal distance of the nearest limited-access freeway to the station entrance, in feet.

Demographic Variable

HHINCOME	Annual household income for households within station catchment area, 1990. Measured using GIS. Source: 1990 census STF-3A.

An entropy index of land-use mixture was also used as a candidate predictor variable. Using data from the Association of Bay Area Governments, the shares of land area within a one (CBD stations) or two mile (all other stations) radius of stations that is devoted to commercial, office, residential, industrial, and institutional uses were determined. (Data are broken down by hectare grid-cells; using GIS buffers, the proportions of total area within each land use were determined.) An entropy value close to one indicates heterogeneous land use compositions whereas a value close to zero indicates virtually all land is devoted to a single use.

Pricing Variables

According to economic theory, the demand for transit should also be influenced by the price of its chief competitor, the private automobile. No price variables for competitive modes were used, however, since the differentials between these prices and those charged for transit trips would be similar across all stations (assuming a standard cost per automobile mile of travel was used). Additionally, research shows that most automobile travelers do not weigh full costs when making automobile trips, but rather are most cognizant of direct, out-of-the-pocket costs. In general, including price variables for competitive modes is only necessary when a longitudinal analysis is being conducted and the influences of factors like changing fuel prices over time need to be considered.

Economic theory holds that, all else being equal, demand declines as prices increase. Two price variables were included in the analysis. One measures, for each of the 34 BART stations, the average adult cash fare to the remaining 33 stations that was charged in the spring of 1990. Because there was not significant variation across the stations, a second price variable was included — the weekday adult cash fare from each station to the downtown San Francisco Montgomery Street station, one of the busiest and most central stations on the system. It should be noted that since BART employs distance-based fares, this variable also serves as a proxy for the distance of a station from downtown San Francisco, the Bay Area's dominant CBD.

Bus Services

Another factor influencing transit demand is service levels. During any time of the day, most BART stations receive similar service levels, so including this as a predictor variable in a cross-sectional model is problematic. In a longitudinal analysis, adjustments would need to be made for changing service intensity over time, however the lack of significant variation in a cross-sectional study precludes including measures of direct service level.

The transit service variable that does vary significantly across stations is the route miles of feeder bus service. Feeder buses complement rail services and thus should contribute positively to rail ridership. A bus route was considered to be a feeder service if one of its stops was within 200 feet of a station entrance.

In addition, some bus services compete with rather than complement rail services. These are generally services that operate parallel to rail lines, often on major arterials one or more blocks away. As shown in Table 1, the route miles of parallel bus services were included as a predictor variable to reflect this competitive influence.

Transportation Supply Variables

Other features of transportation supply that are thought to shape transit demand are parking supplies, whether a station is a terminal or not, and the proximity of the nearest freeway. Nearly all suburban BART stations are surrounded by large parking lots, meaning they are able to draw passengers from a larger catchment area. Terminal or near-terminal stations, moreover, also tend to have large catchments since they are the first stations reached by those living beyond rail corridors.

Demographic Variable

The only demographic variable used in these analyses was the annual 1990 household income for households within station catchments.

2.2 Anticipated Relationships

Table 2 postulates the expected statistical relationship between each of the ridership variables and predictor variables considered in this analysis. Density and land area are expected to positively influence ridership levels and rates. The effects of mixed land uses, however, is unclear. Mixed uses are thought to exert their greatest influence on access trips to rail stations — e.g., they can encourage walking from reasonably close by residences to stations. At the station-to-station, or corridor, level, however, their influences are likely fairly weak. Whether they would encourage rail riding is unclear. On the one hand, having mixed uses in station areas might induce some to opt for rail transit for convenience reasons. On the other hand, to the degree that mixed uses obviate the need for rail travel in the first place, they could be negatively associated with ridership.

Price can clearly be expected to exert a negative influence on ridership. One must invoke the *ceteris paribus* assumption, however. Transit ridership rates, for example, might very well be high for distant stations where high average fares are paid; however, controlling for distance and other features of these trips, the marginal contributions of higher fares should be to reduce ridership rates.

As noted, feeder buses complement rail services and thus should be positively associated with ridership. The partial correlation of ridership rates and parallel route miles, however, should be negative.

Parking supply and terminal locations (which often have large parking supplies and frequent feeder bus services) should be positively correlated with ridership rates. The effects of freeway proximity, however, are difficult to foretell. On the one hand, being close to a freeway could drain away transit ridership by providing an alternative line-haul route. On the other hand, being close to a freeway means that those who are park-and-riding have easier access to stations, particularly suburban stations.

Table 2. Anticipated Sign of Partial Correlation between Ridership and Independent Variables

	Anticipated Sign
Land Use Variables	
EMPDENS	+
POPDENS	+
AREA	+
ENTROPY	?
Pricing Variables	
AVGFARE	-
CBDFARE	-
Complementary and Competing Bus Service Variables	
FEEDER	+
PARALLEL	-
Transportation Supply Variables	
PARKING	+
TERM_NT	+
FWYPX	+/-
Demographic Variable	
HHINCOME	+/-

Lastly, the likely influence of household incomes on ridership is also difficult to postulate. Transit is often thought of as an inferior good, thus ridership should decline with income. However, this relationship holds less for large metropolitan areas with serious traffic congestion problems; in these places, the San Francisco Bay Area included, rail transit often becomes a legitimate and convenient means of travel, especially to major downtowns. Additionally, since most heavy rail systems are radial, designed to funnel suburbanites to downtown, and since many downtown San Francisco workers have well-paid office jobs, the association between income and ridership might be positive. Indeed, ridership surveys reveal that BART's peak hour customers average higher incomes than the Bay Area average.

3.0 Models of BART Ridership

3.1 Total Weekday Ridership

Table 3 reveals that, controlling for the land area of the catchment zone as well as other factors, employment density increases total passenger trips (turnstile entries and exits) for BART stations. Holding all other factors constant, an increase of 10 workers per acre for a one to two mile radius from a station is associated with 1,430 more daily rail trips. Interestingly, mixed land uses were negatively associated with rail patronage, controlling for other factors. This suggests that any benefits of mixed land use are unlikely to be registered on the line haul segment of trips; instead, most benefits should be associated with access trips, such as revealed in the Topic 3 report.

Consistent with expectations, feeder bus services increase rail ridership and higher fares lower ridership. Every ten route miles of service within a station's catchment is, on average, associated with 1,662 more daily trips to that station, removing the influences of all other factors.

Overall, a fairly good predictive model was derived for total ridership. Over 92 percent of the variation in total ridership was predicted by the five variables shown in Table 3. All of the predictor variables were statistically significant at the .05 probability level.

3.2. Total Weekday Ridership, Log-Log Form

Fairly similar relationships were found when the model was expressed in log-log form, as shown in Table 4. Although the R-squared statistic declined slightly, the ability to produce coefficients in elasticity form is a significant advantage of this model. Based on the elasticities, ridership appears to be only moderately sensitive to changes in density and feeder bus services. Demand is significantly more sensitive to fare levels — on average, around three times as much as it is to employment densities or feeder bus service levels.

Two additional variables entered the log-log model of total weekday ridership — household income and the terminal/near-terminal dummy variable — and one of the variables from Table 3, the entropy land-use mixture index, failed to enter the model. Household income was positively associated with total ridership, meaning once factors like size of catchment zone and fare levels are controlled for, the tendency is for residents of higher income households to patronize BART more. This no doubt reflects the high share of downtown San Francisco office workers who commute via BART each workday. And as expected, being a terminal or near-terminal station induces transit ridership once factors like catchment zone size are controlled for. (Terminal stations average relatively large catchment zones, so the controls are important here.) This suggests that the convenience of terminal stations to many suburban, exurban, and rural households that patronize BART to reach the core of the region leads to relatively high ridership levels.

Table 3. Regression Model Predicting Total Weekday Passenger Trips (Entries and Exits) at BART Stations, 1990

Dependent Variable: Total Weekday Passenger Trips (Entries and Exits) at Station, 1990

Variable	Coefficient	Standard Error	T Statistic	Probability
EMPLOYMENT DENSITY: Employees per acre within one mile radius of downtown stations and two mile radius of all other stations, 1990	143.476	17.435	8.229	.000
LAND AREA: Catchment area accounting for 90% of access and egress trips to station, in square miles, 1990	7.558	3.006	2.551	.016
LAND-USE MIXTURE: Entropy index of land-use mixture within one mile radius of downtown stations and two mile radius of all other stations, 1990[1]	-10261.721	4696.646	-2.185	.037
FEEDER BUS SERVICE: Total route miles of feeder bus services (within 200 feet of station) for station catchment area, 1990	166.198	32.085	5.180	.000
FARE TO SAN FRANCISCO CBD: One-way adult cash fare from station to Montgomery Street Station, 1990	-4375.408	1244.743	-3.515	.001
CONSTANT	17255.308	3365.033	5.128	.000

SUMMARY STATISTICS:

R^2 = .924
F = 67.953, prob. = .000
No. of cases = 34

Note:
[1] Entropy = $\{;_i[p_i^{*}\ln(p_i)]\}/\ln(k)$ where p_i = proportion of land area in land-use category i , and k = number of land-use categories. Ranges between 0 and 1, where 0 signifies land devoted to a single use and i signifies land area evenly spread among all uses.

Overall, the key land-use variable that was found to influence total ridership levels on BART was employment density immediate to the station. BART's busiest stations — Montgomery and Embarcadero stations — average 26,000-28,000 customers per day; these stations also have, by far, the highest employment densities, over 200 employees per acre.

The effects of employment density on total ridership levels were plotted for three different fare scenarios — $1, $2, and $3 fares to downtown San Francisco. These scenarios are shown in Figure 1. (All other predictor variables from Table 4 are set at their mean or median values — annual household income of $30,000, catchment area of 80 square miles, and 30 feeder bus route miles.) The plot clearly reveals that ridership rises with employment densities and falls with fares. Assuming a $2 fare, the model predicts around 12,000 weekday passenger trips in settings with 20 employees per acre (e.g., Walnut Creek BART station). At 150 employees per acre (e.g., Embarcadero station) and a $2 fare, the model estimates nearly 20,000 rail trips would be generated by a station.

Ridership levels vary even more with fare levels (as suggested by the elasticity estimates). At 80 workers per acre, a fare of $3 could be expected to produce around 11,500 daily passenger trips; decreasing the fare to $1, however, increases this figure to 26,000.

3.3 Passenger Trips per 1,000 Population

Indexing passenger volumes (entries and exits) by the population of the catchment area provides a more intuitive and transferable output. Table 5 reveals that, consistent with expectations, ridership per capita rises with both population and employment density as well as feeder bus service intensities.

The model reveals that, holding other factors constant, an increase of 10 workers per acre for a radius of one to two miles of a BART station increases the weekday passenger trips by 6.5 per 1,000 population within the ridership catchment. And according to the model, an increase in population density of 1,000 inhabitants per square miles adds an average of 8 more rail trips per 1,000 residents.

Table 4. Regression Model Predicting the Natural Log of Total Weekday Passenger Trips (Entries and Exits) at BART Stations, 1990

Dependent Variable: Natural Log of Total Weekday Passenger Trips (Entries and Exits) at Station, 1990

Variable	Coefficient	Standard Error	T Statistic	Probability
LOG of EMPLOYMENT DENSITY: Natural Log of employees per acre within one mile radius of downtown stations and two mile radius of all other stations, 1990	.2128	.0415	5.121	.000
LOG of LAND AREA: Natural Log of catchment area accounting for 90% of access and egress trips to station, in square miles, 1990	.1604	.0528	3.040	.005
LOG of FEEDER BUS SERVICE: Natural log of total route miles of feeder bus services (within 200 feet of station) for station catchment area, 1990	.2381	.0585	4.067	.000
LOG of FARE TO SAN FRANCISCO CBD: Natural log of one-way adult cash fare from station to Montgomery Street Station, 1990	-.6488	.1109	-5.850	.000
LOG of HOUSEHOLD INCOME: Natural log of annual household income for station catchment 1990	.2287	.1010	2.264	.032
TERMINAL: Terminal or near-terminal station (0=no, 1=yes)[1]	.2680	.1038	2.582	.016
CONSTANT	6.9979	.3300	21.206	.000

SUMMARY STATISTICS:
R^2 = .901
F = 40.637, prob. = .000
No. of cases = 34

Note:
[1] Near-terminal represents stations toward the end of a line that function like terminals because they are closer to freeways than actual terminals and thus serve a larger catchment area. BART's near-terminal stations, El Cerrito del Norte and Pleasant Hill, have larger supplies of parking than terminal stations since they are easier to reach by freeway.

Figure 1. BART Daily Trips by Employment Density, Sensitivity Test of Three Fares Levels for Trips to San Francisco CBD

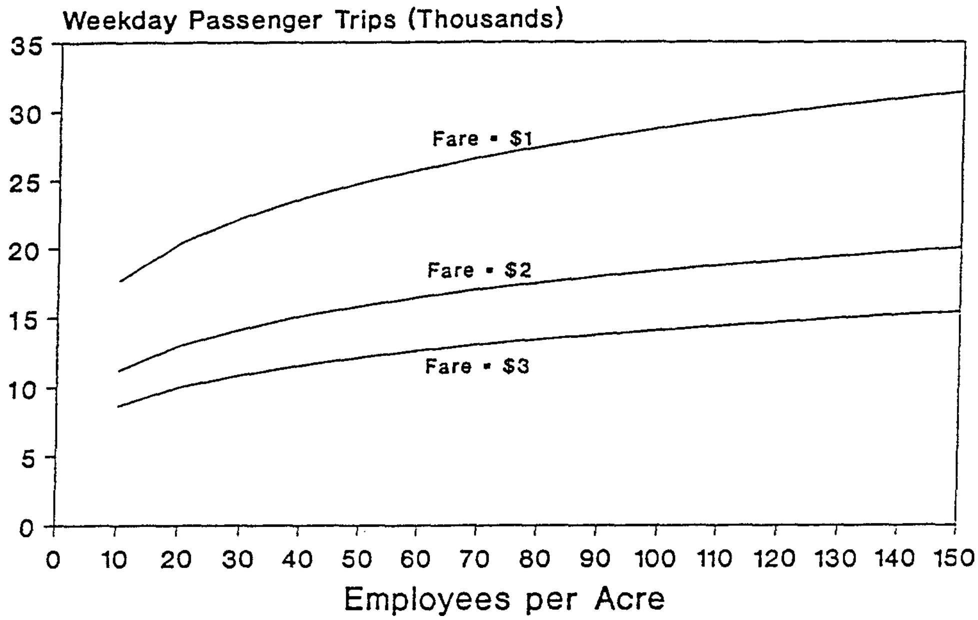


Table 5. Regression Model Predicting Weekday Passenger Trips (Entries and Exits) per 1,000 Population, BART Stations, 1990

Dependent Variable: Weekday Passenger Trips (Entries and Exits) at Station per 1,000 Population in Catchment Area, 1990

Variable	Coefficient	Standard Error	T Statistic	Probability
EMPLOYMENT DENSITY: Employees per acre within one mile radius of downtown stations and two mile radius of all other stations, 1990	.6545	.1814	3.608	.001
POPULATION DENSITY: Population per square mile within station catchment area, 1990	.0080	.0031	2.563	.016
FEEDER BUS SERVICE per 1,000 POPULATION: Total route miles of feeder bus services (within 200 feet of station) per 1,000 population of station catchment area, 1990	1.9849	.4358	4.555	.000
CONSTANT	5.799	13.060	0.444	.660

SUMMARY STATISTICS:

R^2 = .805
F = 41.354, prob. = .000
No. of cases = 34

3.4. Passenger Trips per 1,000 Population, Log-Log Model

Expressing relationships in log-log form produces Table 6. The model again shows that rail trips per capita rises significantly with employment density and feeder bus service intensity. In log-log form, two other significant predictors entered the model: catchment land area and household income. According to the model, the larger the catchment area, the lower the per capita transit-trip making. This likely reflects the influences of population density (which was a significant predictor in Table 5) — larger catchment areas generally average lower population densities, which are in turn associated with lower per capita ridership rates. Consistent with earlier findings, income appears to raise per capita rail trips, controlling for factors like employment density and feeder service intensity.

Interpreting regression coefficients as elasticities, Table 6 reveals that per capita rail travel was most sensitive to changes in income levels, followed by feeder bus service intensities, land area, and lastly, employment densities. All of these relationships are fairly inelastic. Moreover, all are statistically significant at around the .01 probability level. Additionally, the log-log model provided a slightly better fit in predicting per capita rail travel than the linear model.

The sensitivity of rail trips per capita to employment density is revealed in Figure 2. Three levels of feeder service intensity are shown in this graph — 0.25, 0.5, and 1.0 route miles of bus service per 1,000 population within the catchment. (The average value for the 34 BART station catchments was 0.25.) In generating these estimates, the remaining variables in Table 6 were set at the following mean values: catchment land area = 80 square miles and annual household income = $30,000.

The graph underscores the moderate sensitivity of ridership rates to employment density and the somewhat stronger sensitivity to changes in feeder bus service intensity. Assuming an average of one route mile per 1,000 catchment area population, Figure 2 projects that a station area with 120 workers per acre will produce 175 rail trips per 1,000 population, compared to 145 trips per 1,000 population at 20 workers per acre. With service levels at just 0.25 route miles per 1,000 inhabitants, ridership falls to 90 rail trips per 1,000 residents at densities of 20 workers per acre.

3.5. Passenger Trips per Square Mile

The last set of models predict ridership per square mile of station catchment area. Table 7 shows that the predictor variables that entered the model were identical to those in the model for per capita ridership levels (Table 6). Expressing ridership on a square mile basis, however, increased the predictive powers of the model considerably — raising the R-squared statistic to .911.

Table 6. Regression Model Predicting the Natural Log of Weekday Passenger Trips (Entries and Exits) per 1,000 Population, BART Stations, 1990

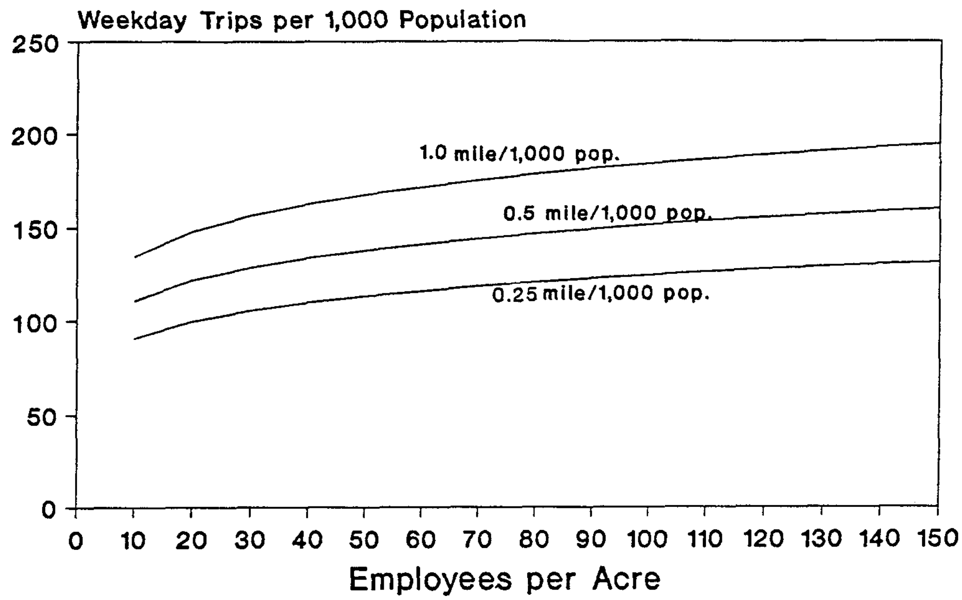
Dependent Variable: Natural Log of Weekday Passenger Trips (Entries and Exits) at Station per 1,000 Population in Catchment Area, 1990

Variable	Coefficient	Standard Error	T Statistic	Probability
LOG of EMPLOYMENT DENSITY: Natural Log of employees per acre within one mile radius of downtown stations and two mile radius of all other stations, 1990	.1351	.0498	2.717	.011
LOG of LAND AREA: Natural Log of catchment area accounting for 90% of access and egress trips to station, in square miles, 1990	-.2413	.0651	-3.710	.001
LOG of FEEDER BUS SERVICE per 1,000 POPULATION: Natural log of total route miles of feeder bus services (within 200 feet of station) per 1,000 population of the station catchment area, 1990	.2831	.0785	3.606	.001
LOG of HOUSEHOLD INCOME: Natural log of annual household income for station catchment, 1990	.3637	.1405	2.717	.011
CONSTANT	4.4128	.4421	10.465	.000

SUMMARY STATISTICS:

R^2 = .833
F = 36.170, prob. = .000
No. of cases = 34

Figure 2. BART Weekday Trips per 1,000 Catchment Area Population, by Employment Density and Bus Route Service Intensity



*Feeder Route Miles per 1,000 Population

Table 7 indicates that increasing employment density by 10 workers per acre raises the number of rail passenger trips in a catchment zone by 21.8 per square mile, holding other factors constant. Every 1,000 person increase in population density, moreover, adds around 53 rail trips per square mile of catchment zone.

Table 7. Regression Model Predicting Weekday Passenger Trips (Entries and Exits) per Square Mile, BART Stations, 1990

Dependent Variable: Weekday Passenger Trips (Entries and Exits) at Station per Square Mile of Catchment Area, 1990

Variable	Coefficient	Standard Error	T Statistic	Probability
EMPLOYMENT DENSITY: Employees per acre within one mile radius of downtown stations and two mile radius of all other stations, 1990	2.184	1.276	1.712	.097
POPULATION DENSITY: Population per square mile within station catchment area, 1990	.0529	.0214	2.476	.019
FEEDER BUS SERVICE per SQUARE MILE: Total route miles of feeder bus services (within 200 feet of station) per square mile of station catchment area, 1990	3.804	.5522	6.888	.000
CONSTANT	-133.134	64.111	-2.077	.047

SUMMARY STATISTICS:

R^2 = .911
F = 10.1699, prob. = .000
No. of cases = 34

8.0 Predictive Model of Passenger Trips per Square Mile, Log-Log Model

The final model predicts passenger trips per square mile in a multiplicative, or log-log, form. This produces a model with explanatory variables similar to those produced from other models, as shown in Table 8. The log-log estimate of trips per square mile was the best-fitting equation (R-squared = .944) and contained a balance of predictor variables related to employment and population density, feeder bus service intensity, and transit fares.

Table 8 reveals greater elasticity between rail ridership rates and density. Rail trips per square mile increased most rapidly with increases in catchment population density — every 10 percent increase in population density was associated with around a 5 percent increase in trips per square mile, holding all other factors constant. In fact, ridership levels expressed on a square mile basis were around twice as sensitive to population densities as they were to employment densities. There appeared to be a moderate degree of sensitivity to feeder bus service intensities and fare levels.

Figure 3 presents a sensitivity analysis for rail trips per square mile as a function of employment density, at three hypothetical fare levels. (All other predictor variables from Table 8 were set at their mean values.) These curves are steeper than those shown for Figure 2, indicating a greater sensitivity of ridership rates to employment densities when ridership is expressed on a square mile basis versus a per capita basis. From Figure 3, we see that at a fare of $2 per trip, the model estimates around 240 rail trips per catchment zone square mile at 100 workers per acre, compared to 160 trips per square mile at just 20 workers per acre. There are relatively greater shifts in ridership rates between the three hypothetical fares, however, underscoring the finding that fare elasticities are higher than employment density elasticities.

The final plot, Figure 4, highlights what was found in the log-log model — that ridership per square mile is most sensitive to catchment area population density. Visually, this is best seen by the relatively steep curves in the graph, much steeper than those generated by any of the previous graphs. Again assuming a fare of $2 (and setting all other predictor variables at their mean values), Figure 4 estimates that there would be nearly 200 trips per square mile for a station with a catchment zone averaging 4,000 residents per square mile; this compares to just 135 trips per square mile for a catchment zone with 2,000 inhabitants per square mile. And at 2,000 persons per square mile, if the average fare were to fall to $1, and all else remained equal, Figure 4 indicates ridership levels would rise again to around 190 rail trips per square mile of catchment area. The most fortuitous scenario for transit would be an average population density of 5,000 residents per square mile and an average fare to downtown San Francisco of $1 — a combination that, the model estimates, would produce over 300 weekday trips per square mile of catchment zone.

Table 8. Regression Model Predicting the Natural Log of Weekday Passenger Trips (Entries and Exits) per Square Mile of Catchment Area, BART Stations, 1990

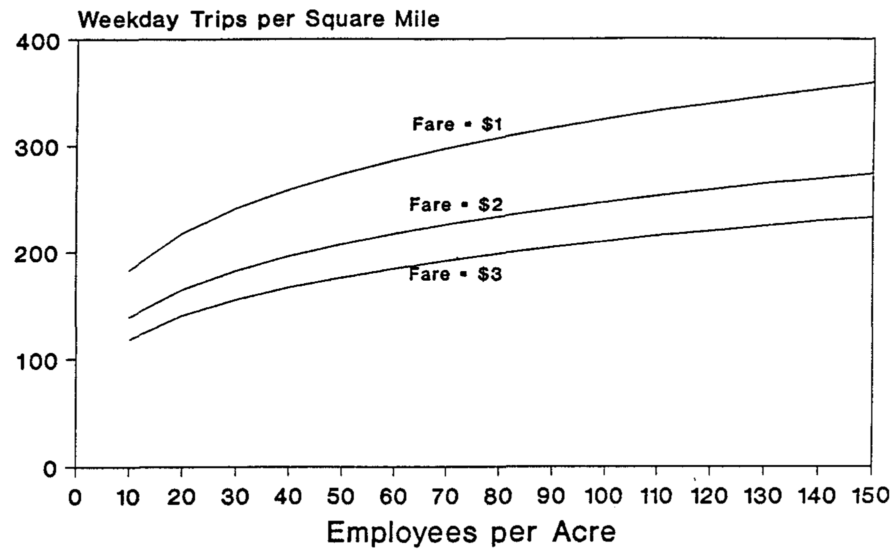
Dependent Variable: Natural Log of Weekday Passenger Trips (Entries and Exits) at Station per Square Mile of Catchment Area, 1990

Variable	Coefficient	Standard Error	T Statistic	Probability
LOG of EMPLOYMENT DENSITY: Natural Log of employees per acre within one mile radius of downtown stations and two mile radius of all other stations, 1990	.2489	.0701	3.549	.001
LOG of POPULATION DENSITY: Natural Log of population per square mile within station catchment area, 1990	.5154	.1695	3.041	.005
LOG of FEEDER BUS SERVICE per SQUARE MILE OF CATCHMENT: Natural log of total route miles of feeder bus services (within 200 feet of station) for station catchment area per square mile of catchment area, 1990	.3503	.1060	3.306	.003
LOG of FARE TO SAN FRANCISCO CBD: Natural log of one-way adult cash fare from station to Montgomery Street Station, 1990	-.3983	.2403	-1.658	.108
CONSTANT	1.169	1.486	0.787	.437

SUMMARY STATISTICS:

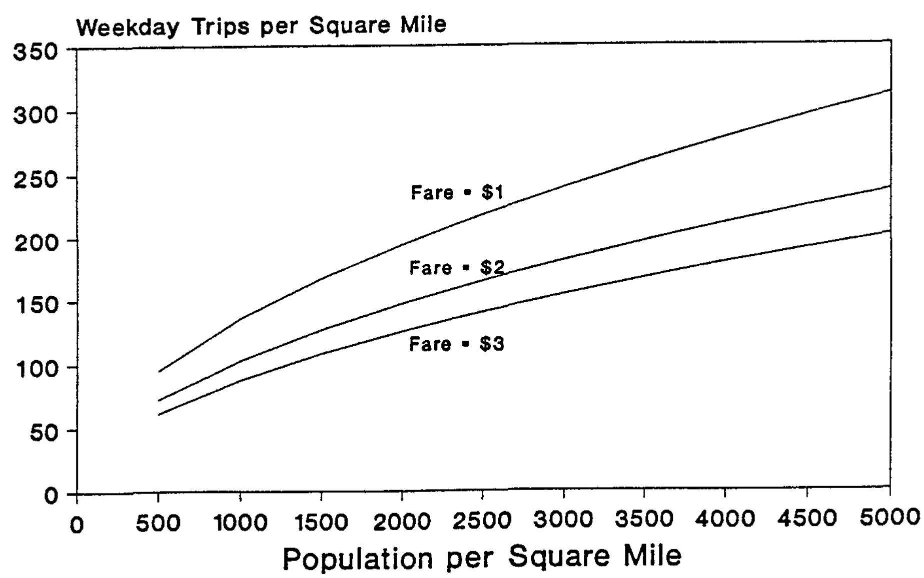
R^2 = .944
F = 121.592, prob. = .000
No. of cases = 34

Figure 3. BART Weekday Rail Trips per Square Mile of Catchment Zone, by Employment Density and Fare to San Francisco CBD



*Fare to San Francisco CBD

Figure 4. BART Weekday Rail Trips per Square Mile of Catchment Zone, by Population Density and Fare to San Francisco CBD



*Fare to San Francisco CBD

9.0 Conclusion

The demand models estimated for the San Francisco BART heavy rail system produced intuitive and consistent results that support accepted economic theories on transit ridership. Both population and employment densities were associated with higher ridership levels and rates. Ridership generally increased even more strongly as a function of feeder bus service intensities. High transit fares, on the other hand, significantly depressed ridership levels. Other, somewhat weaker, contributors to ridership increases were household incomes and the presence of terminal or near-terminal station. Mixed land uses, somewhat surprisingly, were found to lower rail ridership levels, though the relationship here was fairly weak and quite likely reflecting the influences of other, omitted variables.

In general, models presented in multiplicative, log-log form provided the best fit of data, and produce results in the most interpretative form. Additionally, expressing ridership on a per capita or per square mile basis provided output that has most transferability to other rail transit properties in the U.S. In combination with the model results of the main section of this report should provide useful benchmarks for analyzing the sensitivity of rail ridership to the built environment and other factors influencing transit demand.

APPENDIX B

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Comparisons of the National and BART Models With Chicago's Heavy and Commuter Rail

1.0 Introduction

This appendix analyzes the ridership demand for Chicago's CTA rapid rail and Metra commuter rail using the United States models developed in the main report and the BART models developed in Appendix A. Along with the San Francisco Bay Area, the Chicago area is being used for conducting in-depth analyses for several of the research topics. This comparison validates that general demand models work for specific systems and also shows some differences between these specific systems and the general models and BART. Some of these differences are expected since CTA is a rapid rail system and the demand models are only for light rail and commuter rail.

The two Chicago rail systems are

- Metra commuter rail which operates between the suburbs and the downtown Loop
- CTA rapid rail which operates within the city limits.

Full information on the Chicago data sources can be found in the Topic 3 and 4 reports. In order to compare the Chicago systems with the BART model for this analysis, catchment area sizes had to be estimated. Two of the Chicago data sources provide ways to estimate these catchment areas. Using land-use information (residential and employment densities and percent of land used for various purposes), the stations were classified into six clusters for each system (see Topic 3 report). Travel diary information provided the median home-end access distance traveled to each type of station. The median catchment area equals pi times the square of the median distance traveled to stations of the cluster type. Multiplying the catchment area by the population density (two mile density for commuter rail and half mile density for rapid rail) at the station gives the median catchment area population. The above catchment areas are for the median distance (50th percentile) as opposed to the 90th percentile of distance traveled used by Cervero. However, assuming there is a constant relationship between the radii of the two areas will yield equations which are equivalent.

A second possible way to determine catchment areas is from a park and ride survey performed by Metra. This information is only available for commuter rail stations with lots and only relates to automobile travel, but it provides an accurate look at the distance driven to the individual stations. The median distance is used again and the relatively few stations with no park and ride lot are assigned a catchment area of three-quarters of a mile. This provides the median catchment area and median catchment population.

The variables used in the analysis are listed in Table 1.

Table 1: Variable List

Variable	Definition	Log of Variable	
TOTON	Total station boardings	(LOGTOTON)	
ONSPERTP	Boardings per 1,000 people in cluster catchment	(LOGONPTP)	
ONSPERSM	Boardings per square mile in cluster catchment	(LOGONPSM)	
ONSPPRTP	Boardings per 1,000 people in p&r survey catchment	(LOGPRPTP)	Metra only
ONSPPRSM	Boardings per square mile in p&r survey catchment	(LOGPRPSM)	Metra only
RESIDEN2	Persons per acre within two miles of station	(LOGREDE2)	Metra only
HHLDDEN2	Households per acre within two miles of station	(LOGHHDE2)	Metra only
HHLDINC2	Median household income within two miles of stn.	(LOGHINC2)	Metra only
EMPLDENS	Employees per acre within half-mile of station	(LOGEMDEN)	
ENTROPY	Measure of mix between the land uses		
PARKING	Presence of park and ride station		
TERMINAL	Indicator if station is a terminal		
SOMEBUS	Presence of feeder bus service		Metra only
BUSMILES	Mileage of street served by bus within half-mile	(LOGBUSMI)	
DISTCBD	Distance in miles to CBD	(LOGDCBD)	
CBDLDCBD	DISTCBD*LOGDCBD (interacts well with LOGDCBD)		
DISTNEAR	Distance in miles to the next nearest station	(LOGDNEAR)	
CLCATCHA	Catchment area using station cluster	(LOGCLCAT)	
PRCATCHA	Catchment area using P&R survey	(LOGPRCAT)	Metra only

2.0 Comparison with National Model

This section of the report compares Metra to the national commuter rail equation and CTA to the national light rail equation. Metra was one of the systems used in developing that national commuter rail and provided about one-third of the data points. The models should therefore be similar. CTA is not a light rail, but a comparison shows whether ridership on CTA is based on the same or different factors.

The same variables are used here as in the national models except that the national models used employment figures for each CBD. This cannot be done for Metra and CTA because there is only one CBD making this a constant. Instead, the station level employment density is used in each equation. The employment measures are therefore not comparable. Also, the CTA estimation does not include an indicator of feeder bus service since bus service is available near all of the CTA stations. The national models were developed without the downtown stations; the same procedure is followed here.

Metra, No CBD, National CR List of Variables

DEP VAR:Log of Daily Boardings N: 204 MULTIPLE R: 0.558 SQUARED MULTIPLE R: 0.311
ADJUSTED SQUARED MULTIPLE R: .286 STANDARD ERROR OF ESTIMATE: 0.925

VARIABLE	COEFFICIENT	STD ERROR	STD COEF	TOLERANCE	T	P(2 TAIL)
CONSTANT	-3.993	2.521	0.000	.	-1.584	0.115
Parking	0.855	0.257	0.222	0.789	3.327	0.001
Feeder bus	0.140	0.168	0.054	0.827	0.836	0.404
Log of HH income	0.681	0.242	0.239	0.488	2.821	0.005
Log of pop density	-0.091	0.158	-0.073	0.221	-0.576	0.565
Log of miles to CBD	0.772	0.315	0.402	0.131	2.452	0.015
Nonlinear distance	-0.005	0.004	-0.183	0.140	-1.158	0.248
LOG of emp. density	0.244	0.093	0.243	0.410	2.628	0.009

The signs of the significant coefficients are compared below.

	Parking	Feeder Bus	Household Income	Population Density	Distance to CBD	Distance to CBD (non-linear)	Employment
Metra	+		+		+		+
Nat'l CR	+	+	+	+	+	-	+

For Metra, as for commuter rail nationally, park-and-ride lots, higher household incomes, greater distances to the CBD, and higher employment near stations means more riders. Higher bus service levels and population densities do not increase Metra ridership although they do for the national commuter rail set. A non-linear measure of distance to the CBD is not significant for Metra in this equation although it was in other Metra models.

CTA, No CBD, National Light Rail List of Variables

DEP VAR:Log of Daily Boardings N: 127 MULTIPLE R: 0.508 SQUARED MULTIPLE R: 0.258
ADJUSTED SQUARED MULTIPLE R: .221 STANDARD ERROR OF ESTIMATE: 0.711

VARIABLE	COEFFICIENT	STD ERROR	STD COEF	TOLERANCE	T	P(2 TAIL)
CONSTANT	5.483	0.526	0.000	.	10.430	0.000
Terminal	0.804	0.265	0.293	0.663	3.038	0.003
Parking	-0.152	0.243	-0.059	0.686	-0.625	0.533
Log miles to nearest station	0.648	0.151	0.415	0.660	4.291	0.000
Log of miles to CBD	0.275	0.134	0.242	0.447	2.058	0.042
Log of pop density	0.238	0.095	0.231	0.723	2.499	0.014
Log of emp density	0.495	0.104	0.573	0.426	4.757	0.000

The signs of the significant coefficients are compared below:

	Terminal	Parking	Bus Service	Distance nearest station	Distance CBD	Residential Density	Employment
CTA	+		N/A	+	+	+	+
Nat'l LR	+	+	+	+	-	+	+

As with light rail, CTA ridership is greater at stations with higher residential and employment density. In addition stations at the end of the line or with wider spacings have higher ridership in both models. Parking is not significant for CTA, but it is strongly correlated with terminal stations as they are virtually the only stations with parking. Distance to the CBD has opposite signs in the two models. Distance to the CBD is positively related to ridership for CTA unlike in the national light rail model, where stations closer to the CBD have higher ridership after controlling for parking and terminal stations.

This analysis allows us to compare the elasticities of key land use variables from the national models with those for the Chicago systems as shown in Table 2. All of the elasticities are significantly less than one (i.e., a one percent change in the independent variable, say residential density, produces less than a one percent change in rail ridership). Of the density elasticities, CBD employment densities for the commuter rail systems have the most impact. A doubling of CBD employment density (100 percent increase) yields a 71.5 percent increase in commuter rail ridership. The employment density elasticity for the Metra system is much smaller, but it is measuring something quite different. The

Metra elasticities indicate that increasing employment densities near stations outside the CBD will increase ridership somewhat (a doubling of station area employment densities yields almost a 25 percent increase in ridership.) The elasticities for residential densities are higher for light rail systems than they are for commuter rail systems or for the CTA heavy rail system. For commuter rail in general and Metra commuter rail in particular, higher average household income does more to increase ridership than either measure of density. Household income however, was not a significant variable for light rail and, therefore, was not included in CTA analysis.

Table 2. Comparison of Elasticities of Key Land Use Varibles for United States and Chicago System Models

Variable	United States Commuter Rail	United States Light Rail	Metra Commuter Rail	CTA Heavy Rail
Residential Density	0.249	0.592	not significant	0.238
Employment Density*	0.715	0.400	0.244	0.495
Average Household Income	0.877	not significant	0.681	not included

* Employment density for the United States models is for CBD employment. Employment density for the Metra and CTA stations is for station area employment with CBD stations excluded from the analysis.

3.0 Comparison with BART Models

This section of the report compares ridership demand on the CTA and Metra rail systems with that on BART using the BART models developed in Appendix A. There are differences in the way some variable are defined and measured. In the BART analysis, catchment areas were based on the census tracts that produced 90 percent of a station's riders. This type of information was not available for the Chicago riders. Catchment areas are therefore estimated as explained earlier. Secondly, residential density for the Chicago stations is for a area roughly within 2 miles of the stations, while residential density for the BART analysis is for the entire catchment area which is generally much larger. The variable for bus service here only measures the number of miles of nearby service without distinguishing whether it is feeder or competitive service as the BART analysis did.

CBD stations are included in this analysis because they were included in the BART modeling. Some issues related to this are discussed in the conclusions.

Because many of the variables are defined and measured somewhat differently, the following comparisons should be made with caution. They are presented mainly to understand whether the systems are fundamentally the same or different, not to compare the differences in elasticities or other more precise measures. Only the signs of the coefficients are compared although the full regression results are shown as an attachment the differences in elasticities or other more precise measures. Only the signs of the coefficients are compared although the full regression results are shown as an attachment to this appendix. Tables compare the signs of the coefficients of significant variables for BART, Metra, and CTA. Variables significant at the 0.05 level appear as two symbols (i.e. + + or —), while those only significant at the 0.10 level appear as one symbol (i.e. + or -).

Ridership (Linear Model)

	Employment Density	Land Area	Entropy	Bus Service	Distance to CBD
BART	++	++	--	++	--
Metra	++				
CTA	++				

This model does a poor job of predicting Metra or CTA ridership. Only station area employment density is significant.

Ridership (Log - Log Model)

	Employment Density	Land Area	Household. Income	Bus Service	Distance to CBD	Terminal
BART	++	++	++	++	--	++
Metra	++	++	++	--	--	++
CTA		-	++			++

Results for BART and Metra are similar with this model and CTA partially follows the model. The Metra commuter rail and BART have the same set of significant variables for this equation; the only difference is a change in sign for bus service. This may be due to the Metra variable not differentiating between competing and complementary bus service or to differences in feeder bus services between the systems. For all three systems, ridership increases with household income. More riders get on at terminal stations in all three systems as well. Only three of the six variables—land area, household income, and terminal station—are significant in explaining CTA ridership. The same factors apparently do not explain ridership on the older, urban CTA heavy rail system and the newer BART system that extends out into the suburbs.

Riders per Thousand People (Linear Model)

	Employment Density	Population Density	Bus Service
BART	++	++	++
Metra	++	--	++
CTA	++	-	-

All three of the variables are significant for Metra, but population density has the opposite sign of BART. Curiously, bus service near Metra stations agrees in sign with the BART model in this case. This model apparently does not work well for CTA. It says that CTA ridership is inversely related to population density, the opposite result of most analysis for the CTA system.

Log of Riders per Thousand People (Log - Log Model)

	Employment Density	Land Area	Bus Service	Household. Income
BART	++	--	++	++
Metra	++	--	--	++
CTA	++	--		++

Again, the Metra system resembles BART. All of the BART variables are significant for Metra although bus service again has the opposite sign from BART. CTA has a reasonable match with BART as well, agreeing in significance and sign with all variables but bus service.

Riders per Square Mile (Linear Model)

	Employment Density	Population Density	Bus Service
BART	+	++	++
Metra	++	-	
CTA	++	++	

Metra again shows the opposite effect of population density from the BART, and this time CTA has the expected positive sign on population density. Bus service levels are not significant for Metra or CTA.

Log of Riders per Square Mile (Log - Log Model)

	Employment Density	Population Density	Bus Service	Distance to CBD
BART	++	++	++	--
Metra	++		-	--
CTA	++	++		

As usual, employment densities are positively related to ridership for all three systems. In this model, Metra ridership is not influenced by population densities, while CTA ridership has the expected positive sign. Both BART and Metra have declining ridership with distance from the CBD (because CBD stations are included in the analysis), but distance does not affect CTA ridership levels.

4.0 Conclusions for BART, Metra, and CTA Comparisons

As in the BART analysis in Appendix A, the multiplicative (log-log) models provide better results. The linear models sometimes produce results that are the opposite of what was expected or inconsistent with other analysis done with the Chicago data.

This comparison indicates that BART is more like the Metra commuter rail system than the urban CTA rail system. All of the variables from the BART model are significant and all but bus service have the same sign for Metra in the log-log models of ridership and riders per thousand population. In both of these models, there are fewer significant explanatory models for CTA.

Each of the analyses in Topic 1 measures employment density in a different way, yet in every case, employment density does matter. In the national models of the main report, employees per acre are only measured for the CBD. In the previous analysis of Metra and CTA system using the national models, employment density is measured for a 0.5 mile circle around each station—excluding CBD stations. In the BART analysis (and the Metra and CTA analysis using the same models)—employment density is measured around all stations whether inside or outside the CBD. The basic conclusion is that more jobs per acre in CBDs, near stations within CBDs, and in station areas outside CBDs all boost ridership on rail systems.

Overall, residential and employment densities do influence rail systems boardings, but other factors such as household income and characteristics of the rail system also are influential.

Attachment to Appendix B

Regression Results for Metra and CTA Using BART Models

Metra, CBD In, BART List (Boardings)

DEP VAR: TOTON N: 213 MULTIPLE R: 0.857 SQUARED MULTIPLE R: 0.734
ADJUSTED SQUARED MULTIPLE R: .727 STANDARD ERROR OF ESTIMATE: 2265.262

VARIABLE	COEFFICIENT	STD ERROR	STD COEF	TOLERANCE	T	P(2 TAIL)
CONSTANT	736.709	773.350	0.000	.	0.953	0.342
EMPLDENS	130.127	6.848	0.887	0.590	19.004	0.000
PRCATCHA	0.078	4.786	0.001	0.948	0.016	0.987
ENTROPY	-1150.379	1095.123	-0.039	0.956	-1.050	0.295
BUSMILES	-8.966	16.600	-0.032	0.364	-0.540	0.590
DISTCBD	15.168	19.166	0.038	0.549	0.791	0.430

CTA, CBD In, BART List (Boardings)

DEP VAR: TOTON N: 144 MULTIPLE R: 0.420 SQUARED MULTIPLE R: 0.176
ADJUSTED SQUARED MULTIPLE R: .146 STANDARD ERROR OF ESTIMATE: 2805.287

VARIABLE	COEFFICIENT	STD ERROR	STD COEF	TOLERANCE	T	P(2 TAIL)
CONSTANT	2346.473	2642.986	0.000	.	0.888	0.376
EMPLDENS	9.176	4.156	0.402	0.180	2.208	0.029
CLCATCHA	59.321	149.421	0.037	0.678	0.397	0.692
ENTROPY	-2067.642	2474.556	-0.072	0.797	-0.836	0.405
BUSMILES	9.974	28.905	0.088	0.093	0.345	0.731
DISTCBD	99.253	125.299	0.132	0.217	0.792	0.430

Metra, CBD In, BART List (Boardings)

DEP VAR:LOGTOTON N: 213 MULTIPLE R: 0.622 SQUARED MULTIPLE R: 0.387
ADJUSTED SQUARED MULTIPLE R: .369 STANDARD ERROR OF ESTIMATE: 0.992

VARIABLE	COEFFICIENT	STD ERROR	STD COEF	TOLERANCE	T	P(2 TAIL)
CONSTANT	-7.555	2.269	0.000	.	-3.329	0.001
LOGEMDEN	0.344	0.098	0.347	0.305	3.511	0.001
LOGPRART	0.366	0.061	0.371	0.784	6.025	0.000
LOGBUSMI	-0.290	0.129	-0.207	0.350	-2.238	0.026
LOGDCBD	-0.540	0.139	-0.358	0.352	-3.896	0.000
LOGHINC2	1.393	0.211	0.437	0.682	6.614	0.000
TERMINAL	0.756	0.324	0.134	0.898	2.330	0.021

CTA, CBD In, BART List (Log Boardings)

DEP VAR:LOGTOTON N: 144 MULTIPLE R: 0.573 SQUARED MULTIPLE R: 0.328
ADJUSTED SQUARED MULTIPLE R: .299 STANDARD ERROR OF ESTIMATE: 0.716

VARIABLE	COEFFICIENT	STD ERROR	STD COEF	TOLERANCE	T	P(2 TAIL)
CONSTANT	-0.013	1.811	0.000	.	-0.007	0.994
LOGEMDEN	-0.006	0.122	-0.011	0.108	-0.051	0.960
LOGCLCAT	-0.197	0.115	-0.167	0.521	-1.718	0.088
LOGBUSMI	0.041	0.135	0.032	0.445	0.305	0.761
LOGDCBD	-0.134	0.151	-0.176	0.124	-0.884	0.378
LOGHINC2	0.765	0.183	0.418	0.490	4.175	0.000
TERMINAL	0.721	0.249	0.234	0.752	2.895	0.004

Metra, CBD In, BART List (Boardings / Thousand People)

DEP VAR:ONSPPRTP N: 213 MULTIPLE R: 0.712 SQUARED MULTIPLE R: 0.507
ADJUSTED SQUARED MULTIPLE R: .500 STANDARD ERROR OF ESTIMATE: 404.633

VARIABLE	COEFFICIENT	STD ERROR	STD COEF	TOLERANCE	T	P(2 TAIL)
CONSTANT	7.734	51.739	0.000	.	0.149	0.881
EMPLDENS	11.729	1.297	0.607	0.525	9.044	0.000
RESIDEN2	-14.509	4.979	-0.180	0.619	-2.914	0.004
BUSMILES	6.124	2.893	0.166	0.383	2.117	0.035

CTA, CBD In, BART List (Boardings / Thousand People)

DEP VAR:ONSPERTP N: 144 MULTIPLE R: 0.562 SQUARED MULTIPLE R: 0.316
ADJUSTED SQUARED MULTIPLE R: .301 STANDARD ERROR OF ESTIMATE: 479.940

VARIABLE	COEFFICIENT	STD ERROR	STD COEF	TOLERANCE	T	P(2 TAIL)
CONSTANT	507.744	149.578	0.000	.	3.395	0.001
EMPLDENS	3.126	0.649	0.725	0.215	4.815	0.000
RESIDEN2	-5.605	2.906	-0.144	0.871	-1.929	0.056
BUSMILES	-6.111	3.170	-0.284	0.226	-1.928	0.056

Metra, CBD In, BART List (Log Boardings / Thousand People)

DEP VAR:LOGPRPTP N: 213 MULTIPLE R: 0.625 SQUARED MULTIPLE R: 0.391
ADJUSTED SQUARED MULTIPLE R: .379 STANDARD ERROR OF ESTIMATE: 1.243

VARIABLE	COEFFICIENT	STD ERROR	STD COEF	TOLERANCE	T	P(2 TAIL)
CONSTANT	-10.744	2.799	0.000	.	-3.839	0.000
LOGEMDEN	0.404	0.105	0.323	0.414	3.839	0.000
LOGPRARt	-0.595	0.072	-0.478	0.866	-8.214	0.000
LOGBUSMI	-0.715	0.161	-0.403	0.353	-4.428	0.000
LOGHINC2	1.520	0.249	0.378	0.764	6.100	0.000

CTA, CBD In, BART List (Log Boardings / Thousand People)

DEP VAR:LOGONPTP N: 144 MULTIPLE R: 0.759 SQUARED MULTIPLE R: 0.576
ADJUSTED SQUARED MULTIPLE R: .564 STANDARD ERROR OF ESTIMATE: 0.922

VARIABLE	COEFFICIENT	STD ERROR	STD COEF	TOLERANCE	T	P(2 TAIL)
CONSTANT	-4.008	2.330	0.000	.	-1.720	0.088
LOGEMDEN	0.383	0.092	0.411	0.315	4.174	0.000
LOGCLCAT	-0.619	0.140	-0.321	0.581	-4.434	0.000
LOGBUSMI	-0.060	0.159	-0.028	0.533	-0.375	0.708
LOGHINC2	0.794	0.220	0.266	0.565	3.618	0.000

Metra, CBD In, BART List (Boardings / Square Mile)

DEP VAR:ONSPPRSM N: 213 MULTIPLE R: 0.867 SQUARED MULTIPLE R: 0.752
ADJUSTED SQUARED MULTIPLE R: .749 STANDARD ERROR OF ESTIMATE: 1239.466

VARIABLE	COEFFICIENT	STD ERROR	STD COEF	TOLERANCE	T	P(2 TAIL)
CONSTANT	-8.981	158.487	0.000	.	-0.057	0.955
EMPLDENS	70.760	3.973	0.847	0.525	17.812	0.000
RESIDEN2	-28.336	15.251	-0.081	0.619	-1.858	0.065
BUSMILES	6.128	8.862	0.038	0.383	0.691	0.490

CTA, CBD In, BART List (Boardings / Square Mile)

DEP VAR:ONSPERSM N: 144 MULTIPLE R: 0.653 SQUARED MULTIPLE R: 0.427
ADJUSTED SQUARED MULTIPLE R: .414 STANDARD ERROR OF ESTIMATE: 2802.288

VARIABLE	COEFFICIENT	STD ERROR	STD COEF	TOLERANCE	T	P(2 TAIL)
CONSTANT	-1276.103	873.357	0.000	.	-1.461	0.146
EMPLDENS	15.062	3.791	0.548	0.215	3.973	0.000
RESIDEN2	66.696	16.966	0.270	0.871	3.931	0.000
BUSMILES	22.479	18.508	0.164	0.226	1.215	0.227

Metra, CBD In, BART List (Logs Boardings / Square Mile)

DEP VAR:LOGPRPSM N: 213 MULTIPLE R: 0.512 SQUARED MULTIPLE R: 0.263
ADJUSTED SQUARED MULTIPLE R: .248 STANDARD ERROR OF ESTIMATE: 1.290

VARIABLE	COEFFICIENT	STD ERROR	STD COEF	TOLERANCE	T	P(2 TAIL)
CONSTANT	6.595	0.696	0.000	.	9.472	0.000
LOGEMDEN	0.431	0.122	0.366	0.332	3.539	0.000
LOGREDE2	-0.149	0.154	-0.086	0.446	-0.967	0.335
LOGBUSMI	-0.365	0.183	-0.218	0.295	-1.991	0.048
LOGDCBD	-0.687	0.162	-0.383	0.437	-4.249	0.000

CTA, CBD In, BART List (Log Boardings / Square Mile)

DEP VAR:LOGONPSM N: 144 MULTIPLE R: 0.660 SQUARED MULTIPLE R: 0.436
ADJUSTED SQUARED MULTIPLE R: .420 STANDARD ERROR OF ESTIMATE: 0.925

VARIABLE	COEFFICIENT	STD ERROR	STD COEF	TOLERANCE	T	P(2 TAIL)
CONSTANT	5.314	0.985	0.000	.	5.393	0.000
LOGEMDEN	0.497	0.119	0.612	0.188	4.170	0.000
LOGREDE2	0.345	0.108	0.218	0.870	3.200	0.002
LOGBUSMI	-0.118	0.171	-0.064	0.465	-0.689	0.492
LOGDCBD	-0.137	0.182	-0.127	0.143	-0.754	0.452

APPENDIX C

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List of Light Rail and Commuter Rail Lines

Commuter Rail

city	line[1]	# of stations[2]	length[3]	boardings[4]
Boston	Attleboro	8	35.2	9388
Boston	Fitchburg	17	46.1	3811
Boston	Framingham	9	13.3	4682
Boston	Franklin	12	21.3	5603
Boston	Haverhill	13	28.4	3594
Boston	Ipswich	3	6.9	755
Boston	Lowell	7	20.0	4057
Boston	Needham Hts	9	8.7	3539
Boston	Readville	4	7.1	1028
Boston	Rockport	13	28.4	4630
Boston	Stoughton	2	3.1	1530
Chicago	BN	24	30.5	24867
Chicago	C&NW-N	24	45.0	13969
Chicago	C&NW-NW	20	56.1	19530
Chicago	C&NW-W	15	27.0	13880
Chicago	Elec-Blue Island	7	3.3	1130
Chicago	Elec-Main Line	23	22.2	16092
Chicago	Elec-S Chicago	8	3.9	3039
Chicago	Heritage	5	24.8	677
Chicago	Milwaukee-N	17	43.1	10425
Chicago	Milwaukee-W	21	33.9	11076
Chicago	RI-Main Line	13	30.4	9066
Chicago	RI-Beverly	12	5.8	6113
Chicago	South Shore	2	4.5	1752
Chicago	SWS	8	13.3	2869
Los Angeles	Orange County	8	77.9	1407
Los Angeles	Riverside	4	31.9	1224
Los Angeles	San Bernardino	10	43.7	2578
Los Angeles	Santa Clarita	8	71.9	2723
Los Angeles	Ventura	9	60.2	1639
Miami[5]	Tri-Rail	13	64.0	7279
Philadelphia	SEPTA-1235	5	4.9	2857
Philadelphia	SEPTA-2N	7	7.1	1483
Philadelphia	SEPTA-2S	16	20.7	3451
Philadelphia	SEPTA-3N	13	20.5	2921
Philadelphia	SEPTA-3S	14	11.8	4020
Philadelphia	SEPTA-5N	17	21.2	3824
Philadelphia	SEPTA-5W	23	38.8	12256
Philadelphia	SEPTA-6S	3	1.2	206

city	line[1]	# of stations[2]	length[3]	boardings[4]
Philadelphia	SEPTA-6W	12	14.4	1892
Philadelphia	SEPTA-7N	11	23.4	3738
Philadelphia	SEPTA-7W	10	5.1	2310
Philadelphia	SEPTA-8N	5	3.8	1928
Philadelphia	SEPTA-8W	10	5.8	1650
San Francisco	Caltrain	31	74.9	15073
Toronto[6]	6501E	9	20.0	13655
Toronto[6]	6501W	11	33.0	15878
Toronto[6]	6521	7	18.0	6621
Toronto[6]	6531	7	23.0	3943
Toronto[6]	6561	4	7.0	2561
Toronto[6]	6565	5	20.0	857
Toronto[6]	6571	7	19.0	1239
Washington DC	Brunswick	16	66.5	3155
Washington DC	Camden	10	30.5	1765
Washington DC	Penn	12	67.6	5840
Total		613	1470.1	307075

Light Rail

city	line[1]	# of stations[2]	length[3]	boardings[4]
Baltimore	MTA-N	7	8.1	3826
Baltimore	MTA-S	9	7.5	6207
Boston	Green-B	22	4.0	32979
Boston	Green-C	13	2.3	12727
Boston	Green-D	13	9.1	18124
Boston	Green-E	7	1.8	13451
Buffalo	Metro Rail	8	4.6	14440
Calgary [6]	NE	7	5.1	16180
Calgary [6]	NW	6	3.3	15140
Calgary [6]	S	7	6.4	18610
Cleveland	Blue	11	3.2	1440
Cleveland	Blue/Green	6	4.2	2550
Cleveland	Green	11	3.5	1350
Edmonton [6]	101	4	3.4	12274
Los Angeles	Blue	18	19.0	28360
Philadelphia	Media	33	8.3	3578
Philadelphia	Sharon Hill	16	3.5	1251
Pittsburgh	42	12	9.0	22818
Pittsburgh	47	8	10.9	5263
Portland	MAX	19	13.6	14460
Sacramento	RT-E	8	5.2	6542
Sacramento	RT-N	8	5.7	5328
San Diego	East	12	14.8	11982
San Diego	South	11	12.6	18554
St. Louis	MetroLink	9	8.6	11024
Total		285	177.7	298458

[1] Some lines have been broken into segments.
[2] The number of stations within each line segment
[3] The distance in miles from the furthest station in the segment to the nearest station in the segment.
[4] Total daily boardings of stations within the segment
[5] Data from Miami's rail system was not included in the demand analysis because it resembles an intercity line more than a CBD-oriented commuter rail.
[6] Data from Canadian rail system was not included in the demand analysis because employment and demographic data could not be obtained.

APPENDIX D

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Description of Data Collection and Processing for Demand Analysis

Five types of data were assembled with each station used as an observation:

1) Station identification information
2) Station ridership information
3) Transportation service characteristics
4) Population characteristics near station
5) CBD employment information

Each of the variables considered are identified in the following pages. Variables in italics are indicator variables, where a positive response is coded as a "1" and a negative response as a "0". Many other variables are included in the database, but the most significant are provided here to conserve space. Variables are also converted to the their natural logarithms. Variable names which appear in **bold** have logged equivalents which are used as well. The name given to the logged value appears in parentheses at the end of the variable description.

Information on the precise location of stations was determined from maps; travel times and service frequencies were determined from schedules. Follow-up calls to the transit operators generally filled in missing data.

1) Station identification information

The following variables help to uniquely identify each station, and also include some general classifying variables. This information is generally available from transit maps provided by the contacted agencies.

TYPE$	Coded 'LR' for light rail and 'CR' for commuter rail, to allow for different analysis between the two modes.
CITY$	Name of the central city on the line.
LINE$	Line that the station is located on. This is sometimes expanded to distinguish two different corridors. For example, Baltimore has two 'lines', one coded 'MTA-N' and one coded 'MTA-S'.
STATION$	Station name. Sometimes different sources give different names for the same station, but consistent names were adopted.
CANCODE	Is station in Canada? Allows comparisons between the countries.
INCBD	Is station very close to or inside the CBD? Stations where this is true are not included in the analysis. These are typically the CBD station for commuter rail systems and stations within a 'ride-free zone' for light rail systems. (If the classification is not straight-forward, light rail stations within one mile of the CBD and commuter rail stations within three miles are considered to be 'incbd'.)
DUPE	Has this stations already appeared earlier in the database? The database originally coded a station twice if two different lines pass through it. This variable identifies these stations so that analysis can also be done on unique stations.

2) Station ridership information

Boarding and alighting information was asked for by time of day and direction of travel. Only about half of the systems provided that level of detail. To use as many stations as possible, total boardings at each station are employed, regardless of time of day and direction traveled were used. Some of the data dated from the late 1980s while others are as recent as mid-1994. Most are the result of one-day counts. Some cases required slight computations to put the numbers into the proper form (i.e., divide total monthly boardings at a station by the appropriate factor).

INON	If known, daily inbound boardings; otherwise total daily boardings.
INOFF	If known, daily inbound alightings; otherwise, if known, total daily alightings.
OUTON	If known, daily outbound boardings.
OUTOFF	If known, daily outbound alightings.
TOTON	Total daily boardings. **(LOGTOTON)**

3) Transportation service characteristics

Since the means of reaching stations affects the ability to draw from a wider commutershed, data was collected for the amount and availability of parking at the stations and the amount and availability of bus services that can feed the stations from a broader area. Because the terminal station might be expected to draw from a larger area than other stations, this too is accounted for. Competition comes from other stations, either on the same line (next nearest station) or competing lines (competing rail lines), so a variable to reflect the presence of a nearby rail transit line is noted.

TIMECBD	Time in minutes to CBD. Some interpolation needed for the cases where the schedule only includes a few time points. (**LOGTCBD**)
DISTCBD	Distance in track-miles to CBD. (**LOGDCBD**)
DISTIN	Distance in track-miles to next inbound station. (**LOGDIN**)
DISTNEAR	Distance in track-miles to nearest adjacent station. (**LOGDNEAR**)
PEAKNUM	Number of inbound trains run through the station in the AM peak hour (7AM - 8AM). (**LOGPEAKN**)
DAYNUM	Total daily number of inbound trains run through the station. (**LOGDAYN**)
TERMINAL	Is this station the final one on the line? Yes = 1, no = 0
PARKING	Does this station have park-and-ride facilities? Yes = 1, no = 0
SPACES	Number of park-and-ride spaces available. (**LOGSPACE** - set to zero if no parking)
PARKRATE	Utilization rate of park-and-ride spaces.
SOMECOMP	Is there any competing service from nearby rail lines? Yes = 1, no = 0.
BUSSERV	Coded "0" for no feeder bus service, "1" for some service, and "2" if the station is a major transfer point.
SOMEBUS	Is there any feeder bus service? Yes = 1, no = 0

4) Population characteristics near station

Data was gathered from the US Census Bureau's 1990 Summary Tape File 3A (STF3A) which includes basic socio-economic data at a census tract level. Census tract maps were used to locate stations and two types of catchment areas were created around the station. The first is an oblong shape that extended two miles on either side of the station and two miles away from the CBD, but extended one mile towards the CBD. This area is believed to generally include about 70% of the trips to the stations and takes into account that people tend to travel toward the CBD to get to a station. The second catchment area is a simple half-mile radius around the station. Census tracts were then used to approximate this shape. However, because of the sometimes irregular shape of census tracts, it was often difficult to arrive at a good approximation of this half-mile ring. In rural areas, the tracts are quite large and the area included sometimes extends more than two miles from the station. Some judgment was exercised to decide whether to include tracts at the boundaries of these areas.

In downloading the STF3A files from a central database, some small gaps in the data were found. These gaps were typically filled with information from other sources or from typical averages. Canadian census information could not be obtained electronically. From a Canadian government depository, census tract maps were copied and the residential population and area of each noted. No additional socio-economic information was obtained at the Canadian tract level.

The relationship among population density, income and distance from the core of a metropolitan area bears upon the matter of transit ridership. While it is postulated that higher population density results in higher transit use, the lower incomes associated with higher population densities may also have a bearing, as might the fact that higher density areas tend to be closer to the core. In the case of commuter rail the high cost of this high amenity service suggests that an income variable be tested. The Census data's median household income for the two-mile commutershed is used.

POPTWO	Population over STF3A tracts within two-mile oblong area.
AREATWO	Acreage over STF3A tracts within two-mile oblong area. In theory this number should be approximately 6,500 acres, but the true acreage varies considerably.
DENSTWO	Population density over STF3A tracts within two-mile oblong area. (**LOGDENTW**)
POPHALF	Population over STF3A tracts within half-mile of station.
AREAHALF	Acreage over STF3A tracts within half-mile of station. In theory this number should be approximately 500 acres, but the true acreage varies considerably.
DENSHALF	Population density over tracts in half-mile of station. (**LOGDENHA**)
AVGCAR	Average cars per household of tracts in two-mile oblong area. (**LOGAVCAR**)
PCT01CAR	Percent of households in two-mile oblong area which own 0 or 1 car.
AVGHHINC	Average of median household incomes of tracts in two-mile oblong area. (**LOGAVINC**)

5) CBD employment information

Employment information for Central Business Districts is difficult to obtain with accuracy. Published sources of information are available only at a county level. Other sources which are reported on a small area basis, exclude workers not covered by social security, including government workers and the self-employed. A data vendor provided the "covered" employment at a ZIP code level. To address the matter of missing employees, state employment agencies were contacted to determine the percent of government workers in the Metropolitan Statistical Area, and CBD employment was adjusted upward to account for them. Typical percentages were in the 15 percent range, higher for state capitals.

The definition of the CBD proved to be a substantial problem, given the need to rely on ZIP code areas as the building blocks. To define the CBD, a combination of employment density ("covered" employees divided by gross area), the distribution of employees by industry type, and knowledge of the CBD by the researchers was used. The employment and area data for ZIPs was obtained for a rather expansive definition of ZIPs based on local knowledge. Then ZIP "candidates" were eliminated by examining the mix of industries, and the fall off of employment densities from the highest density ZIP. A ZIP was generally excluded if it increased CBD employment by less than half the percentage that it increased acreage if its inclusion resulted in the percent of the land area of the CBD. For example, at the margin, if a ZIP added 40 percent to the land area of the CBD, but only 15 percent to its employment, then the ZIP was not included. However, if the ZIP contained more than 25 percent of the CBD employment if it were included, it was generally retained. In borderline cases the industry mix was referred to; ZIPs with relatively high shares in the financial sector, usually associated with CBDs, suggested inclusion for that ZIP in the CBD definition.

Generally, ZIPs that were removed represented large land areas on the fringe of the CBD with a high share of heavy industry uses and/or residential areas. ZIPs in larger cities tend to be smaller, allowing the CBDs to be more precisely defined. The ZIPs included in each of the CBDs as defined for this study are listed on the next page.

Once the CBD was defined, both employment size (number of employees) and the employment density was calculated. Employment was factored up to account for the county-wide ratio of covered to total employment. Canadian employment information could not be located, making it impossible to include the three Canadian cities in the analysis.

TOTEMPS Employment using CBD data factored for government employees. (**LOGTOTEM**)
EMPACRES CBD ZIP code acreage. (**LOGEMPAC**)
EMPDENS CBD employment density, in employees per gross acre. (**LOGEMPDE**)

List of Zip Codes Included in CBDs

Baltimore
21201
21202

Boston
02108
02109
02110
02111
02114
02116

Buffalo
14202
14203

Chicago
60601
60602
60603
60604
60606
60611

Cleveland
44114
44115

Los Angeles
90013
90014
90015
90017
90071

Pittsburgh
15219
15222

Philadelphia
19102
19103
19106
19107

Portland
97204
97205
97209

Sacramento
95814
95816

St. Louis
63101
63102
63103

San Diego
92101

San Francisco
94102
94103
94104
94105
94108
94111

Washington D.C.
20001
20004
20005
20006
20036
20500

APPENDIX E

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Characteristics Of Hypothetical Rail Corridors, Figures 17-46

All characteristics of corridors were chosen to encompass the range of existing data, or extend slightly beyond them.

Actual CBD employment sizes ranges from 60,000 in Sacramento to 419,000 in Chicago. (See Figure 13 in the text for details.)

CBD employment densities are defined with each employment size in combination with assumed CBD land area, with low density CBDs covering three square miles and high density CBDs covering two square miles. There are no precise definitions of CBDs, but using our definitions which were based on zip codes and employment levels (See Appendix D), we can identify several CBDs in this range of sizes. Portland, Boston, and Chicago are examples of cities with CBDs of about two square miles. Los Angeles and Washington, DC have CBDs that cover about three square miles. Philadelphia, Baltimore, San Francisco, and Buffalo are between these sizes. Some CBDs are much more spread out than these. Sacramento and Cleveland have CBDs that cover more than six square miles.

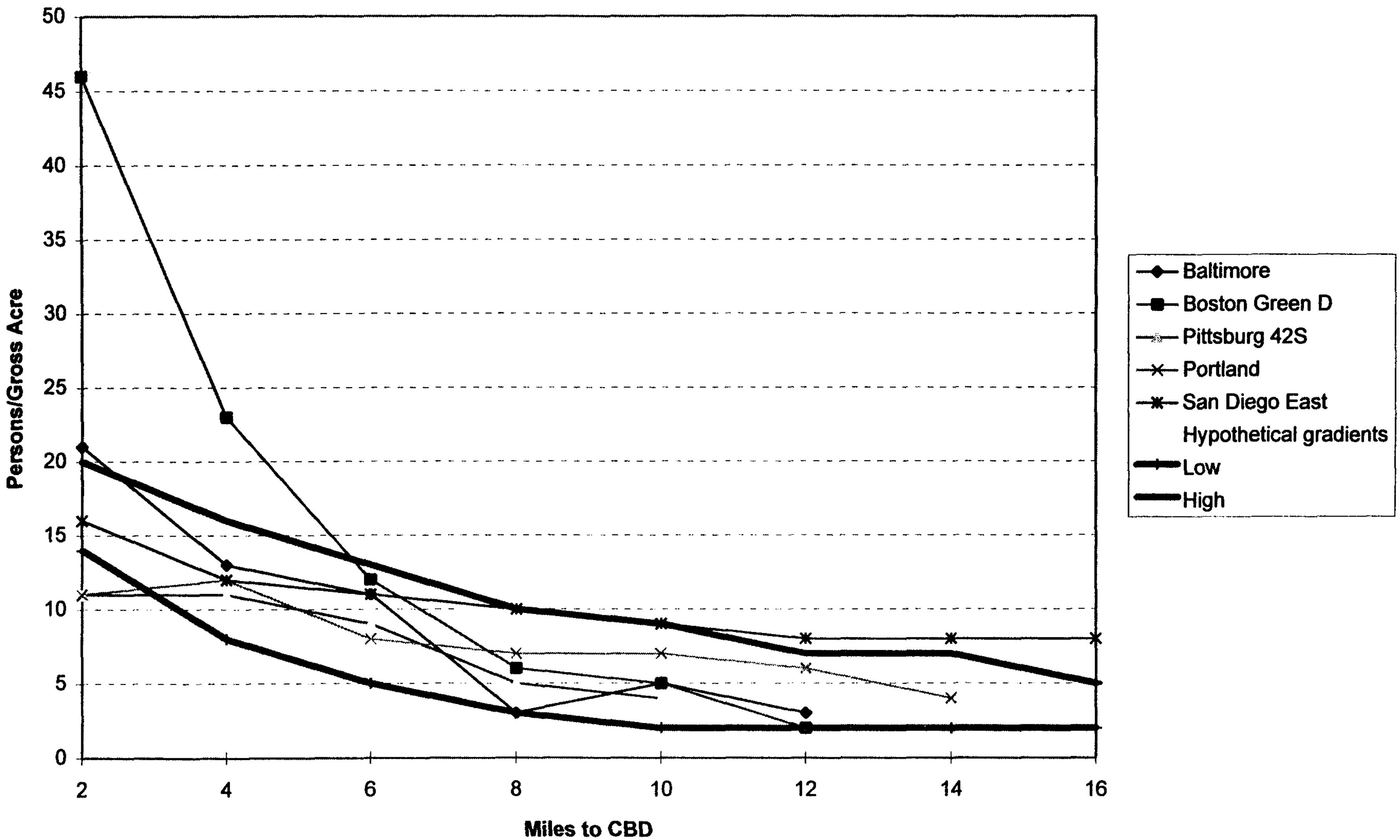
Residential density gradients were hypothesized to reflect the range of conditions in current cities with rail systems. The following figures illustrate a sample of existing light rail and commuter rail density gradients plus the upper and lower extremes of hypothetical gradients (in wider width).

Most of the light rail gradients lie between the assumed high and low extremes. Boston is an exception because residential densities are much higher near the CBD than hypothesized. It is not anticipated that cities adopting light rail today will be as dense as Boston. San Diego is also an exception being more dense than the hypothesized limits at greater distances from the CBD. San Diego illustrates the shallow gradient hypothesized for potential commuter rail in large western cities.

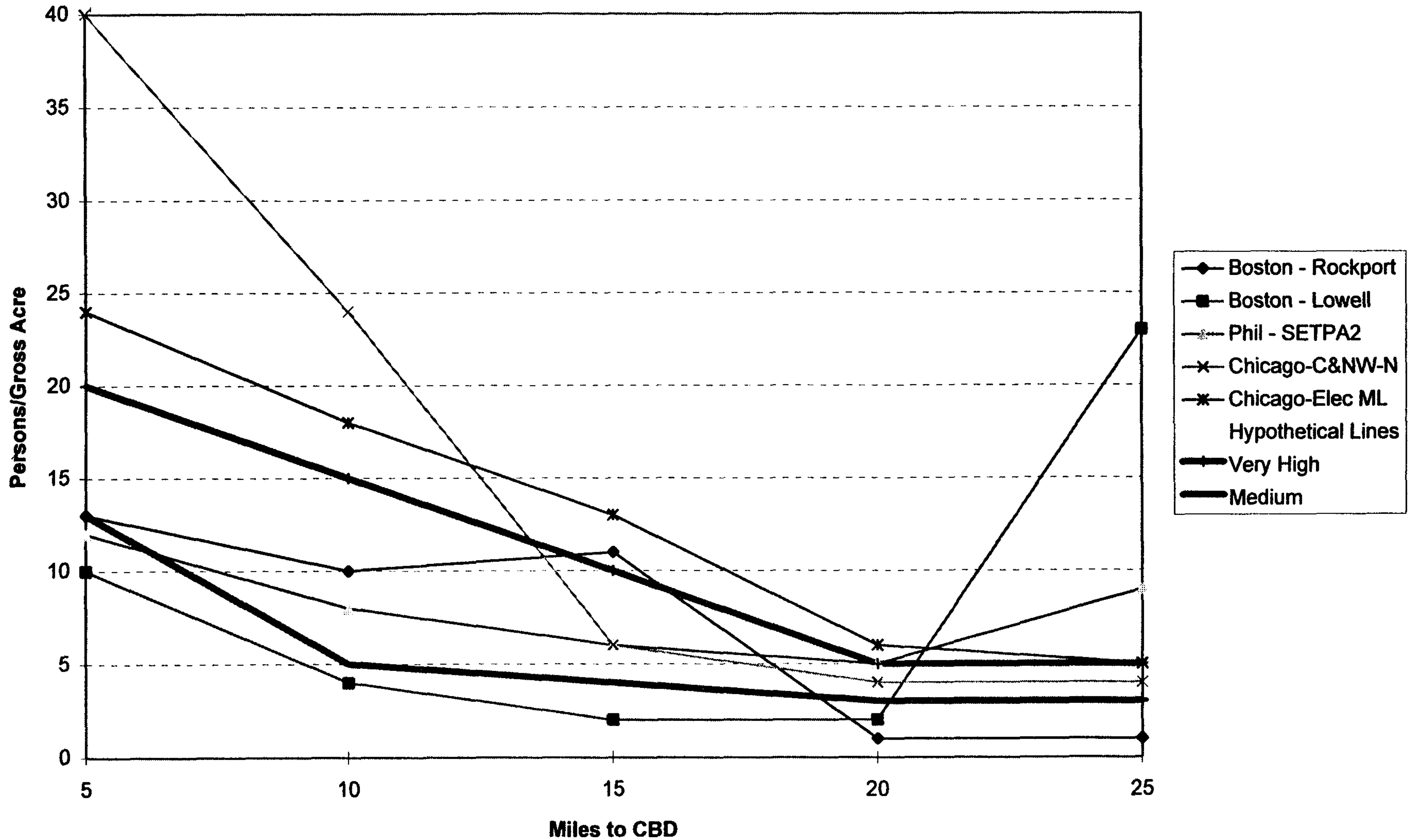
Commuter rail density gradients show more variability. Chicago commuter rail often operates in denser residential areas than the hypothesized very high gradient. However, it is not anticipated that new commuter rail cities will be as dense as Chicago. Some commuter rail systems also operate for at least part of their routes at lower densities than assumed by the medium density gradient. The Boston-Lowell line illustrates a situation not reflected in the hypothesized density gradients—a commuter rail line that terminates in a fairly dense community. In considering these gradients, it is helpful to remember that residential density gradients proved to have little impact on commuter rail ridership and that when considering commuter rail, site specific analysis will be needed.

The average access pattern is intended to reflect the percentages found in Table 5 in the text. Other access pattern assumptions are shown in the following tables.

Light Rail Density Gradients



Commuter Rail Density Gradients



Station Access Modes in Hypothetical Corridors

Light Rail

Miles from CBD	Type 1 Average Park	Type 1 Average Bus	Type 2 Parking Emphasis Park	Type 2 Parking Emphasis Bus	Type 3 Bus Emphasis Park	Type 3 Bus Emphasis Bus
1		x				x
2		x				x
3			x			x
4		x	x			x
5	x		x			x
6		x	x	x		x
7			x			x
8	x	x	x			x
9			x			x
10		x	x	x	x	x
11	x	x	x			x
12			x			x
13	x	x	x			x
14						x
15	x	x	x	x	x	x
16	x	x	x			x
17	x	x	x			x
18	x	x	x			x
19	x	x	x			x
20	x	x	x	x	x	x
21	x	x	x			x
22	x	x	x			x
23	x	x	x			x
24	x	x	x			x
25	x	x	x	x	x	x

Note: Type 1: Average is based on the typical pattern of park-and-ride and feeder bus service of light rail systems studied in this project.

Type 2: Parking Emphasis increases the number of stations with parking and decreases the number with feeder bus service.

Type 3: Bus Emphasis does the opposite. The number of stations with parking decreases and the number with feeder bus increases to all stations.

APPENDIX E (continued)

Commuter Rail

Miles from CBD	Type 1 Average		Type 2 More Bus, Less Park		Type 3 More Bus		Type 4 Less Park	
	Park	Bus	Park	Bus	Park	Bus	Park	Bus
3		x		x		x		x
6	x	x		x	x	x		x
9	x		x	x	x	x	x	
12	x	x		x	x	x		x
14	x	x	x	x	x	x	x	x
16	x			x	x	x		
18				x		x		
20	x	x	x	x	x	x	x	x
22	x	x		x	x	x		x
24				x		x		
26	x	x	x	x	x	x	x	x
28	x			x	x	x		
30	x		x	x	x	x	x	
35	x			x	x	x		
40	x	x	x	x	x	x	x	x
45	x			x	x	x		
50	x	x	x	x	x	x	x	x
55	x			x	x	x		
60	x	x	x	x	x	x	x	x
65	x			x	x	x		
70	x		x	x	x	x	x	
75	x			x	x	x		
80	x	x	x	x	x	x	x	x

Note: Type 1: Average is based on the typical pattern of park-and-ride and feeder bus service of commuter rail systems studied in this project.

Type 2: More bus, less park decreases the number of stations with parking and puts feeder bus service at all stations.

Type 3: More Bus has parking at the same stations as Type 1 but has bus service at every station.

Type 4: Less Park has feeder bus at the same stations as Type 1 but has parking at fewer stations than Type 1.

APPENDIX F

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Light Rail and Commuter Rail Cost Models

This appendix documents the data collection and model development process used to arrive at formulas for predicting light rail transit and commuter rail operating/maintenance and capital costs. Also included as attachments at the end of this appendix are a series of tables listing various cost, ridership, operating and physical characteristics for the various U.S. commuter rail and light rail transit systems investigated in developing the cost models. Light rail transit operating/maintenance and capital costs are covered first followed by similar sections for commuter rail.

Light Rail Transit Cost Models

The Federal Transit Administration (FTA) Data Tables and Transit Profiles series of reports, both based upon 1993 Section 15 Reports from the National Transit Database, served as the two primary sources of information on operations, maintenance, capital costs and other physical characteristics. Three FTA reports also provided input to the analysis process: Estimation of Operations and Maintenance Cost for Transit Systems (DOT-T-93-2, dated December 1992); Characteristics of Urban Transportation Systems (DOT-T-93-07) dated September 1992); and Light Rail Transit Capital Cost Study (dated April 5, 1991). In addition, requests for data were sent to several light rail transit properties in an attempt to supplement missing or incomplete FTA data. Together, these data sources were employed to select U.S. light rail transit systems that could be used to for developing cost models.

Light Rail Operations and Maintenance Costs

A predetermined general framework was employed for developing a series of operating and maintenance cost models based on the physical characteristics of the rail system. This approach used a two step process in which the labor requirements, in terms of the number of workers by various categories, was first estimated, and then the total operating and maintenance costs were computed based on the labor costs per worker and the relationship between non-labor costs and system annual revenue vehicle miles. The process of estimating worker requirements before arriving at dollar costs for operations and maintenance represents an enhancement of the methodology outlined in *Urban Rail in America* (Pushkarev, Zupan, and Cumella, 1980).

Of the light rail transit properties for which some information was available, 12 U.S. systems were selected as both reasonably representative of the operating and maintenance conditions that would be proscribed for a system built today and for which the necessary data was available. These 12 light rail transit systems are found in Baltimore, Boston, Buffalo, Cleveland, Los Angeles, Philadelphia, Pittsburgh, Portland, Sacramento, San Diego, San Francisco, and San Jose. The system in St. Louis was too new to obtain comparable operating and maintenance data. In addition, three Canadian systems, Calgary, Edmonton and Toronto, were initially identified for their representative operating and maintenance conditions. However, difficulty in obtaining the necessary comparable cost and physical characteristics data, combined with differences in Canadian real income levels and currency exchange rate issues, resulted in their disqualification for purposes of developing the cost models. (See Tables 1-5 in the Light Rail Attachments for specific line information.)

Table 6, "Light Rail Transit Operations & Maintenance Costs and Related Characteristics," summarizes the universe of data available and applicable for developing the light rail transit operating and maintenance cost models (see also light rail transit Tables 1-5). An important criterion in the model development was that the input data or explanatory variables selected for the models be confined to information that a sketch planner would reasonably be expected to have for a proposed system in order to maximize the usefulness and application of the models. Using the data from Table 6 (including transformations of this data), linear regression models were proposed and tested for the number of vehicle operations workers, vehicle maintenance workers, way and structures workers, and administrative/existing capital workers. The first three worker categories tended to vary with certain physical characteristics of the transit system, an expected result for labor which is largely a variable cost.

In some cases, two different yet reasonable explanatory variables that were highly correlated could not both be used in a single model due to the problem of multicollinearity. For example, annual revenue hours of service and annual revenue miles of service have different meanings and units (magnitudes), yet comparing across systems, these two variables are highly correlated, i.e., one is close to a linear function of the other. As a result, both variables could not be used in a model to predict the number of vehicle operations workers. In most cases of potential multicollinearity, the choice of which variable to include was obvious from *a priori* expectations and/or cost theory. In a few cases of very similar variables, the one that provided the best fit in the regression model was used.

The equations for the number of workers by labor category resulting from the regression models are provided below in Exhibit 1, along with summary equations converting labor requirements to labor and total O&M dollars. More detailed information about the regression model results can be found at the end of Light Rail Attachment.

The model for vehicle operations workers proved to be a straightforward linear relationship of the number of vehicles operating in maximum service, the annual revenue hours of service and the average vehicle speed, with an adjusted R-squared of 0.965. This means that 96.5 percent of the variation in the number of vehicle operations workers is accounted for by the three explanatory variables. The first two explanatory variables capture that more vehicles and/or more hours of service require more workers. Average vehicle speed further adds the productivity effects of the system: faster speeds yield quicker trips, which means a vehicle and its workers can start a new trip sooner, hence the inverse relationship between workers and speed, as fewer workers are required with more frequent trips. Vehicle maintenance workers was determined to be a linear function of the fleet size, annual revenue hours of service, and the number of track miles per fleet vehicle, with an adjusted R-squared of 0.926. The larger the fleet, the more hours of service provided by the fleet, and/or the higher the average number of miles traveled per vehicle all lead to higher maintenance worker requirements.

Exhibit 1: Light Rail Transit Operation and Maintenance Cost Model Equations

Number of Vehicle Operations Workers =	31.43	+	1.93	×	Number of Vehicles in Maximum Service
		+	0.280	×	Annual Revenue Hours of Service (in 1,000s)
		+	-2.81	×	Average Vehicle Speed (mph)
Number of Vehicle Maintenance Workers =	-43.24	+	0.884	×	Number of Vehicles in Fleet
		+	0.212	×	Annual Revenue Hours of Service (in 1,000s)
		+	35.61	×	Number of Track Miles per Vehicle in Fleet
Number of Way & Structure Maint. Workers*	-64.54	+	3.02	×	Number of Track Miles
		+	61.41		If Average Station Spacing is Less than ½ mile.
Number of Administrative & Capital Staff =	-31.39	+	0.826	×	Number of Track Miles
		+	0.667	×	Annual Revenue Miles (in 1,000s) per Vehicle in Fleet
Summary Formula for Light Rail Transit O&M Labor Requirements =	-107.75	+	0.492	×	Annual Revenue Hours of Service × 1,000
		+	3.85	×	Number of Track Miles
		+	35.61	×	Number of Track Miles per Vehicle in Fleet
		+	1.93	×	Number of Vehicles in Maximum Service
		+	0.884	×	Number of Vehicles in Fleet
		+	0.667	×	Annual Revenue Miles (in 1,000s) per Vehicle in Fleet
		+	-2.81	×	Average Vehicle Speed (mph)
		+	61.41		If Average Station Spacing is Less than ½ mile.
Summary Formula for Light Rail Transit O&M Labor Costs (1993 $) =	**$ 66,004**	**×**	**Total Light Rail O&M Labor Requirements**		

Where $66,004 is the Average O&M Labor Cost per Worker (1993 Dollars, Geographic Cost of Living Normalized)

Summary Formula for Light Rail O&M Non-Labor Costs (1993 $) =	**$1,342,000**	**+**	**1,441**	**×**	**Annual Revenue Miles (in 1,000s)**
Summary Formula for Tatal Light Rail O&M (Labor & Non-Labor) Costs =	**The Sum of the Above Two Amounts**				

*-333.01 for Philadelphia per dummy variable to correct for track miles maintained but no longer in service.

Way and structures workers was a bit more difficult to model across the 12 system sample. The size of the system as measured in track miles proved to be the best explanatory variable for predicting way and structures workers, although number of crossings, average station spacing, number of stations and directional route miles were also investigated. Multicollinearity problems prevented adding any of these variables to a model based on track miles with the exception of a factor to account for close station spacing. The resulting model thus included track miles and an adjustment factor increasing the number of way and structures workers when the average station spacing was less then one-half mile, with an adjusted R-squared of 0.809. This model also included a dummy variable for the Philadelphia system to account for track miles that continue to be maintained but are no longer in revenue service.

Development of a model for predicting the number of administrative and capital workers based upon the physical characteristics of the rail system proved to be a challenging task. There is likely to be a considerable fixed cost component to the need for administrative workers that does not necessary vary directly with hours or miles of service, station spacing, or number of vehicles. In addition, ridership trends, fare collection operations, marketing and information services all likely contribute to administrative worker requirements, but represented data that was either not uniformly available for the system used to develop the models or would not be included in the information available to the sketch planner using the resulting models. In the end, variables were chosen based upon their ability to serve as proxy measures for other attributes believed to be more closely tied to administrative costs. The model for administrative and capital workers was determined to be a linear function of the number of track miles in operation to capture the magnitude of the physical system requiring administration as well as the annual number of revenue miles of service traveled per vehicle in the system's fleet, which attempts to capture how intensely the systems resources requiring administration are employed.

Using the four models described above, the total worker requirements for a proposed light rail transit system can be calculated. This labor requirement can then be multiplied by an average labor cost per worker to arrive at total labor costs. Based upon the 12 system sample, the average labor cost per worker, inclusive of benefits and adjusted for geographic cost of living differences, was calculated at $66,004 in 1993 dollars. Intracity cost of living adjustments were made using the American Chamber of Commerce Researchers Association (ACCRA) Cost of Living Index. The application of the cost of living adjustment to the existing sample systems provided a better calibration "fit" when using the model values for workers to estimate the actual dollar labor costs for the 12 sample systems.

Once non-labor costs are added, annual operating and maintenance costs can be fully estimated. To account for the non-labor costs, which are largely energy expenditures, the relationship between non-labor costs and annual revenue vehicle miles of service was examined. A linear regression model indicated that 63 percent of the variation in non-labor costs was explained by annual revenue vehicle miles and a constant term representing a fixed cost component.

Light Rail Transit Capital Costs

Of the 12 U.S. systems used to develop the operating and maintenance cost models, four systems are too dated for their capital costs to be useful in estimating costs for new systems. As a result, construction and related development costs for the eight most recently constructed light rail transit lines in the United States were used for purposes of developing a capital cost model. These eight light rail transit system lines are listed below.

- Baltimore Central Line
- Los Angeles Blue Line
- Pittsburgh South Hills Line
- Portland Banfield Line
- Sacramento Starter Line
- St. Louis Initial Line
- San Diego South Line
- San Jose Guadeloupe Line

This sample represents the more recent development trends in light rail systems and in composite are representative of the new systems that may be considered in cities planning or evaluating the potential for light rail transit. The unit cost and the application cost model resulting from this analysis should provide a test for the reasonableness of conceptual planning-level capital cost estimates and a tool for the preparation of such comparative estimates.

The estimation of capital costs in project planning is usually based on the definition of alignment conditions such as the horizontal and vertical profile, capital asset requirements and the unit cost measures of each asset category. The unique features of the study systems and their impact on capital unit cost can be mitigated by analysis and the development of composite unit cost. The development of the study database concentrated on actual unit capital cost that should be helpful in preparing capital cost estimates for cities considering light rail transit.

Actual construction cost for the eight cities comprising the construction data base were broken down by project category and reflected in 1993 dollars. The categories utilized include:

- Guideway (line and structures)
- Stations (and parking)
- Right-of-Way
- Traction Power
- Train Control, Signals and Communication
- Utilities, Betterments and Mitigation
- Vehicles and Spare Parts
- Fare Collection
- Yard and Shops
- Agency Cost

The analysis of the data from the respective systems was used to arrange the capital cost into these ten categories as consistently as possible and to identify any anomalies that tended to distort the component cost. The sources of data and reference materials included materials from the 1993 National Transit Database, materials supplied by the agencies, materials from an FTA report entitled Light Rail Transit Capital Cost Study (UMTA-MD-08-7001, April 5, 1991) and materials contained in Parsons Brinckerhoff's capital cost files.

Light Rail Transit Table 7 (in the Light Rail Attachment) provides a summary of light rail capital cost and percentage of "as built" cost by category for the eight study cities. The table also reflects the average cost and percentage of total represented by the respective category for the eight cities. In addition to the total cost per component, a unit cost for stations and vehicles was calculated for each system. The cost of fare collection is also expressed on a per station basis and the yard and shop cost are presented as a function of the transit vehicles. A total cost per route mile for each system is reflected at the bottom of the table. The average cost of the systems per route mile is $22.6 million 1993 dollars.

Table 8 presents the capital cost summary of light rail unit cost for the eight study cities. In addition to the unit cost by component, the table presents the percentage of vertical profile for each study city by at-grade, elevated and subway. The resulting average of 86 percent at-grade, 11 percent elevated and three percent cut/subway is used in establishing the representative mix unit measure for guideway and stations in Table 9, Light Rail Transit Conceptual Cost Estimates by System Component, when the vertical profile is not known and only a rough estimate of route length (or miles) is known. The unit cost in Table 9 reflect the adjusted cost necessary to remove system anomalies from the individual system component cost. As an example, the Pittsburgh right-of-way cost include the purchase of the Panhandle Bridge and an existing railroad tunnel under a portion of the CBD. As a result, adjustments were necessary to the right-of-way cost and guideway cost to prevent distorting the unit cost. And finally Table 9 Supplement provides a series of increasingly complex formulas for calculating the capital cost of a proposed light rail system for conceptual mode comparison purposes. A general definition of capital cost components follows this introductory section.

GUIDEWAY COMPONENTS

This component of capital cost includes the track and structural requirements and generally includes: grading, drainage, sub-ballast, ballast, cross ties, fasteners, rail, special trackwork, track structures and supports, traction power pole supports and other miscellaneous items generally included as part of the guideway along the right-of-way. If the number of track miles of each of the three vertical profile types are known (at-grade, elevated or subway), the unit cost provided can be used to estimate the guideway cost. If only the total length of the guideway is known, the unit cost for the representative mix of vertical profiles can be used to estimate the guideway cost or a new composite more representative of the vertical profile anticipated can be created. In this case, the representative mix reflects a weighted average unit price of the eight systems utilized to develop this unit cost: 86 percent at-grade, 11 percent elevated and four percent cut or subway. This category of project cost, exclusive of engineering and design, usually represents from 22 to 30 percent of the total projects capital cost.

STATIONS (AND PARKING)

This component of capital cost includes: platforms, canopies, signage and graphics, lighting, heating, ventilation and air conditioning (where applicable), landscaping, bus drop-off and parking, amenities, access requirements and related cost impacts such as platform length, escalators/elevators, pedestrian access, disability access mode and weather coverage. These unit costs are based on 400'-0" platforms accommodating a four-car train. While serviceable, the station cost represent simple and functional stations in keeping with the light rail concept. In general, the cost are slightly conservative and represent side platform stations.

If the vertical profile of each station has been identified, the respective unit cost can be used to calculate the station capital cost. If the vertical profile is unknown, the unit cost for a representative mix based on the eight systems analyzed can be used in a manner similar to that explained under guideway above. Exclusive of engineering and design, stations represent approximately five to seven percent of the system cost.

The parking cost includes adequate surface parking spaces to accommodate approximately 25 percent of the average daily ridership at the stations out of the CBD core. With an average station spacing of 0.8 miles and an average route length of 22 miles, the parking is concentrated at the stations outside of a five mile radius from the CBD. A 500-car parking lot cost approximately $1,500,000 1993 dollars.

YARD AND SHOPS

The yard and shops component includes the necessary facilities, service vehicles, and tools and equipment to maintain, store, dispatch and operate and maintain the vehicle fleet and maintain the systems ways and structures. The major shop functions include heavy repair, running repair, motor, truck, wheel turning, catenary machine, air conditioning, electronics, communications, car wash/car cleaning, and maintenance of way. The facility also includes the operators facility, ready room and dispatch, central control, a revenue collection center, and the train storage yard.

The unit cost, exclusive of engineering and design, is expressed as a cost per vehicle. This unit cost is applicable for a fleet of 30 to 50 vehicles. As the fleet size increases, the unit cost should decrease. For a fleet of 30 vehicles, a capital cost of $14.1 million results. On average the yard and shop cost represents three to eight percent of the light rail system cost.

RIGHT-OF-WAY

This capital cost category covers all property acquisition and property acquisition related cost such as appraisals, relocation, etc. The unit cost for right-of-way is expressed in terms of cost per track mile and is based on a composite average for the eight systems analyzed. The composite unit cost per route mile was normalized to eliminate the purchase of extraordinary items such as river crossing, tunnels, etc. If the number of acres and a cost per core and urban acre are unknown, the unit cost provides a reasonable proxy for right-of-way cost. Allowances for any known extraordinary cost should be added to the right-of-way estimate.

TRACTION POWER

This component includes: the traction power substations, the catenary poles, brackets, wire, hardware and other miscellaneous items necessary to the conversion and distribution of traction power. The unit cost represents an adjusted average of the eight systems analyzed. Exclusive of design and engineering, this cost generally comprises four to five percent of the projects capital cost.

TRAIN CONTROL, SIGNALS AND COMMUNICATIONS

This component includes: the train control, block signal and communications elements of the systemwide components. The unit cost represents an adjusted average of the eight systems analyzed. Exclusive of engineering and design, these costs generally represent four to five percent of the total project capital cost.

UTILITIES, BETTERMENTS AND MITIGATION MEASURES

Development of a light rail system involves utility relocation and the mitigation of construction and community impacts that are not directly related to the provision of rail service. This component includes a unit cost per track mile to accommodate utility and railroad relocation and betterments, the environmental mitigation measures typically resulting from the EIS process and the roadway, intersection, landscaping, lighting and other amenities resulting from the community involvement and permitting processes. On average this component represents eight to ten percent of the project capital cost. If specific extraordinary cost have been identified for a project, they should be added to the estimate allowance for this category.

VEHICLES AND SPARE PARTS

This component includes the vehicle fleet and the initial order of spare parts. The cost is based on a unit cost for an 80- to 90-foot articulated light rail vehicle with an average seated capacity for 64 people and standing capacity for an additional 64 persons; a loading of about 130 persons. The unit cost is exclusive of engineering and design by the owner or owners representatives. A premium of approximately $200,000 per vehicle should be added for low floor vehicles.

FARE COLLECTION

This component consists of the fare vending, validation, and change machines representing the hardware supporting the "proof of payment" fare collection system. The estimate is based on an average of two sets of equipment per stations. The revenue collection and maintenance equipment is included with the yard and shop estimate. In general, exclusive of engineering and design, this category represents less than one percent of the projects capital cost.

AGENCY COST

This component includes the cost of the owner's staff, owner's representatives, and the general and administrative expenses of the owner. Included are the cost of administration, project management, all studies, engineering and design, construction and procurement management, design support, testing and start-up, insurance, financing fees and other miscellaneous expenses. The unit cost per track mile for this category represents an adjusted composite average for the eight systems analyzed. This cost can also be calculated as a percentage of the nine capital components described above. This category typically represents 25 to 30 percent of the total project capital cost.

Commuter Rail Cost Models

As with the light rail transit systems, the primary data sources included the Federal Transit Administration (FTA) Data Tables and Transit Profiles series of reports, both based upon 1993 Section 15 Reports from the National Transit Database. In addition, requests for data were sent to several commuter rail properties in an attempt to supplement missing or incomplete FTA data. Together, these data sources were employed to select U.S. commuter rail systems that could be used for developing cost models.

Although similar in objective, the development of cost models for commuter rail poses a more difficult task than for light rail transit. Commuter rail systems vary much more widely in their physical characteristics, operations, development and capital costs, and right-of-way. Likewise, there are few standards components in proposing and costing a new commuter rail line or system. This variation makes it difficult to use a relatively small sample of relevant existing systems to develop operating/maintenance and capital cost models for use by planners in predicting the costs of new systems. The methodology employed in developing commuter rail operating/maintenance and capital cost models is described below.

Commuter Rail Operations and Maintenance Costs

The initial approach for predicting commuter rail O&M costs employed the available data for 16 U.S. commuter rail systems in a relatively simple model which estimated dollar costs directly from certain system characteristics. This preliminary approach was taken because much of the desirable operating and physical characteristics data required for a more detailed modeling process, including worker counts by labor category, were not available for all systems. However, it was decided that the two step approach used in the light rail models, where labor requirements in four worker categories are computed first and then converted to O&M dollar costs, was preferable from the standpoint of the model's intended objective and use. Complete data for only 11 systems were available for this latter approach. Worker category relationships for the Boston MBTA system were an order of magnitude too small, indicating the presence of contracted operations and maintenance workers, necessitating the omission of this data, further limiting the data sample to ten observations.

The ten U.S. commuter rail properties used in developing the O&M cost models include rail lines in Baltimore, Boston, Fort Lauderdale/Miami, Hartford, New Jersey, Philadelphia, San Francisco, Washington D.C, four in Chicago, two in Los Angeles and two in New York (see the Commuter Rail Table 6 in the Commuter Rail Attachment for more specific line information).

Table 6, "Commuter Rail Operations & Maintenance Costs and Related Characteristics" summarizes the universe of data available and applicable for developing the commuter rail operating and maintenance cost models. As in the light rail case, an important criterion in the model development was that the input data or explanatory variables selected for the models be confined to information that a sketch planner would reasonably be expected to have for a proposed system in order to maximize the usefulness and application of the models. Using the data from Table 6 (including transformations of this data), linear regression models were proposed and tested for the number of vehicle operations workers, vehicle maintenance workers, way and structures workers, and administrative/existing capital workers.

Exhibit 2. Commuter Rail Operation and Maintenance Cost Model Equations

Number of Vehicle Operations Workers =	30.542	+	1.351	×	Annual Revenue Hours of Service (in 1,000s)
Number of Vehicle Maintenance Workers =			1.265	×	Number of Vehicles in Fleet
Number of Way & Structure Maint. Workers =	(-1.109	+	0.020	×	Number of Track Miles
			0.302	×	Annual Revenue Miles (in 1,000s) per Track Mile)^2
Number of Administrative & Capital Staff =			0.250	×	Total of Non-Adimistrative Workers Above
Summary Formula for Total Commuter Rail O&M Labor Requirements =	1.25 × {		30.542		
		+	1.351	×	Annual Revenue Hours of Service (in 1,000s)
		+	1.265	×	Number of Vehicles in Fleet
		+ (	-1.109		
		+	0.020	×	Number of Track Miles
		+	0.302	×	Annual Revenue Miles (in 1,000s) per Track Mile)^2
Summary Formula for Total Commuter Rail O&M Labor Costs =	**$60,000**	**×**	**Total Light Rail O&M Labor Requirements**		
Where $60,000 is the Average O&M Labor Cost per Worker (1993 Dollars)					
Summary Formula for Total Commuter Rail O&M (Labor & Non-Labor) Costs =	**$84,507**	**×**	**Total Light Rail O&M Labor Requirements**		
Where $84,507 = $60,000/0.71 is the Average Total O&M Cost per Worker					

In some cases, two different yet reasonable explanatory variable that were highly correlated could not both be used in a single model due to the problem of multicollinearity. This problem is particularly prevalent in such a small sample. Where multicollinearity problems arose, the choice of which variable to include was made from *a priori* expectations and/or cost theory. In a few cases of very similar variables, the one that provided the best fit in the regression model was used. Even where multicollinearity was not a problem, the degrees of freedom available with a ten observation sample prevented the development of model with more than one or two explanatory variables.

The equations for the number of workers by labor category resulting from the regression models are provided in Exhibit 2. More detailed information about the regression model results can be found at the end of the Commuter Rail Attachments.

The model for vehicle operations workers proved to be a straightforward linear relationship of the annual revenue hours of service, with an adjusted R-squared of 0.959. This explanatory variable captures the expected positive relationship between vehicle operation workers and total hours of service operation provided. Vehicle maintenance workers was determined to be a linear function of the fleet size, with an adjusted R-squared of 0.973. The equation was forced through the origin to avoid a negative intercept, and an outlier observation (New York Metro North) was dropped. As expected, the larger the fleet, the more maintenance workers required to maintain it.

For the number of workers engaged in maintenance of way and structures, two explanatory variables proved significant in model development — the number of track miles and the annual vehicle-miles per track mile. The logic for this is as follows; the more miles of track and the greater the intensity of use of the track, the more workers required to maintain it. However, larger systems did not necessary require exact proportional increases in way and structures maintenance workers. To correct for this observation and arrive at a reasonably good model fit, the square-root of the number of workers was used in the regression model, with an adjusted R-squared of 0.821.

None of the available data series proved to serve as reasonable explanatory variables for predicting the number of administrative and capital workers. In light of this finding, it was hypothesized that the administrative and capital worker requirement varied directly with the total number of operation and maintenance workers represented in the other three categories. As a result, the number of administrative workers was posed as a direct linear function of the total non-administrative workers in a regression model forced through the origin, where one administrative and capital worker is required for every four non-administrative workers. This hypothesized relationship was very consistent across the ten sample systems.

Using the four models described above, the total worker requirements for a proposed commuter rail line can be calculated. The resulting labor requirement can then be multiplied by an average labor cost per worker to arrive at total labor costs, or an average total O&M cost per worker to yield total operating and maintenance costs. Based upon the ten system sample, the average labor cost per worker, inclusive of benefits was calculated at $60,000 in 1993 dollars. With non-labor costs added in, the average total O&M cost per worker reaches $84,507. The limited sample size and wide variation in the commuter rail system characteristics did not warrant the more involved approach for arriving at non-labor costs used in the light rail transit case.

Commuter Rail Capital Costs

Unlike the all new construction and development cost associated with a planned light rail system, new commuter rail systems are generally developed largely on existing railroad rights-of-way and may share the facilities with other passenger or freight service based on a trackage agreement, operate exclusively on a facility purchased from a railroad and upgraded, or some combination of the two. The identification of a select set of projects for analysis and the subsequent development of unit cost is therefore less valid for commuter rail than it was for light rail as a result of the variables of track ownership introduced. The variables are compounded by the fact that much of the upgrade work resulting from a trackage agreement may be done by railroad work forces and disparate costs associated with railroad labor agreements result.

The analysis of the capital costs for the typical light rail transit system centered around a determination of the set of infrastructure physical characteristics. For the commuter rail capital costs, the focus is on upgrading the facilities of an existing railroad by a new system operator or for a new use. It is assumed that rough quantities for the horizontal and vertical alignment could be obtained from the railroad or an abbreviated field survey. If the quantities are unavailable, a typical unit cost for each project component was developed from the composite physical characteristic of a prototypical system 40 miles long with an average station spacing of 2.8 miles. The sources of data for the analysis included materials from the 1993 National Transit Data Base, materials from the agencies, an FTA report entitled "Characteristics of Urban Transportation Systems (DOT-T-93-07)" dated September 1992, and the records and files of Parsons Brinckerhoff.

The estimation of capital costs in project planning is usually based on the definition of alignment conditions such as horizontal and vertical profile, capital asset requirements and the unit cost measures of each asset category. The development of the study concentrated on unit capital cost that should be helpful in preparing capital cost estimates in other regions considering commuter rail transit.

Table 7, "Commuter Rail Conceptual Capital Cost Estimates by System Component" provides a range of tools for estimating capital cost. Use of the tools is dependent on the quantitative data available at the component and subcomponent level. The capital cost frame work is broken into eight components, supplemented by subcomponents, as follows:

- Trackwork
- Stations and Parking
- Centralized Train Control (CTC), Signals and Crossing Protection
- Site Improvements
- Maintenance and Storage Facility
- Right-of-Way
- Rolling Stock
- Agency Cost

A composite figure of $5.8 million 1993 dollars per route mile results for the development of a prototypical system. This unit cost can be used to estimate capital cost when only a rough route length is known. A more detailed capital cost estimate can be developed by applying the component or subcomponent unit cost to the quantities associated with a planned system. Following is a brief description of the system components:

TRACKWORK IMPROVEMENTS

The subcomponent listing is fairly self-explanatory.

STATIONS AND PARKING

This component of capital cost includes platforms, canopies, signage and graphics, fare collections, lighting, landscaping, bus drop-off and parking, access requirements and related cost impacts such as platform length, escalators/elevators, pedestrian access, disability access mode and weather coverage. These unit costs are based on 800'-0" platforms.

The parking cost includes adequate surface parking spaces to accommodate 80 percent of the average daily ridership at the stations outside of the CBD core. With an average station spacing of 2.8 miles and an average route length of 40 miles, the parking is concentrated at the stations outside a five mile radius from the CBD.

CTC, SIGNALS AND CROSSING PROTECTION

The subcomponent listing is self-explanatory.

SITE IMPROVEMENTS

The subcomponent listing is fairly self-explanatory.

MAINTENANCE AND STORAGE FACILITY

The maintenance and storage facility component includes the necessary facilities, service vehicles, and tools and equipment to maintain, store, dispatch and operate the commuter rail trains. The major shops include heavy repair, truck, wheel turning, machine, air conditioning, electronics, communications, locomotive brake testing, blow down and car wash/car clearing, and maintenance of way. The facility also includes the operators facility, ready room and dispatch, central control, and a revenue collection center and train storage yard.

RIGHT-OF-WAY

This capital cost category covers all property acquisition and property acquisition related cost such as appraisals and relocations. The unit cost for right-of-way is expressed in terms of cost per track mile and is based on a composite average from other systems. The cost excludes the cost of acquisition of the right-of-way from the railroad. This cost needs to be added to the total for right-of-way.

ROLLING STOCK

The subcomponent listing is self-explanatory.

AGENCY COST

This component includes the cost of the owners staff, owners representatives, and the general and administrative expenses of the owners. Included are the costs of administration, project management, all studies, engineering and design, construction and procurement management, design support, testing and start-up, insurance, financing fees, and other miscellaneous expenses.

THE TRANSPORTATION RESEARCH BOARD is a unit of the National Research Council, which serves the National Academy of Sciences and the National Academy of Engineering. It evolved in 1974 from the Highway Research Board, which was established in 1920. The TRB incorporates all former HRB activities and also performs additional functions under a broader scope involving all modes of transportation and the interactions of transportation with society. The Board's purpose is to stimulate research concerning the nature and performance of transportation systems, to disseminate the information that the research produces, and to encourage the application of appropriate research findings. The Board's program is carried out by more than 400 committees, task forces, and panels composed of more than 4,000 administrators, engineers, social scientists, attorneys, educators, and others concerned with transportation; they serve without compensation. The program is supported by state transportation and highway departments, the modal administrations of the U.S. Department of Transportation, and other organizations and individuals interested in the development of transportation.

The National Academy of Sciences is a private, nonprofit, self-perpetuating society of distinguished scholars engaged in scientific and engineering research, dedicated to the furtherance of science and technology and to their use for the general welfare. Upon the authority of the charter granted to it by the Congress in 1863, the Academy has a mandate that requires it to advise the federal government on scientific and technical matters. Dr. Bruce M. Alberts is president of the National Academy of Sciences.

The National Academy of Engineering was established in 1964, under the charter of the National Academy of Sciences, as a parallel organization of outstanding engineers. It is autonomous in its administration and in the selection of its members, sharing with the National Academy of Sciences the responsibility for advising the federal government. The National Academy of Engineering also sponsors engineering programs aimed at meeting national needs, encourages education and research, and recognizes the superior achievements of engineers. Dr. William A. Wulf is interim president of the National Academy of Engineering.

The Institute of Medicine was established in 1970 by the National Academy of Sciences to secure the services of eminent members of appropriate professions in the examination of policy matters pertaining to the health of the public. The Institute acts under the responsibility given to the National Academy of Sciences by its congressional charter to be an adviser to the federal government and, upon its own initiative, to identify issues of medical care, research, and education. Dr. Kenneth I. Shine is president of the Institute of Medicine.

The National Research Council was organized by the National Academy of Sciences in 1916 to associate the broad community of science and technology with the Academy's purpose of furthering knowledge and advising the federal government. Functioning in accordance with general policies determined by the Academy, the Council has become the principal operating agency of both the National Academy of Sciences and the National Academy of Engineering in providing services to the government, the public, and the scientific and engineering communities. The Council is administered jointly by both Academies and the Institute of Medicine. Dr. Bruce M. Alberts and Dr. William A. Wulf are chairman and interim vice chairman, respectively, of the National Research Council.

Abbreviations used without definitions in TRB publications:

AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
FAA	Federal Aviation Administration
FHWA	Federal Highway Administration
FRA	Federal Railroad Administration
FTA	Federal Transit Administration
IEEE	Institute of Electrical and Electronics Engineers
ITE	Institute of Transportation Engineers
NCHRP	National Cooperative Highway Research Program
NCTRP	National Cooperative Transit Research and Development Program
NHTSA	National Highway Traffic Safety Administration
SAE	Society of Automotive Engineers
TCRP	Transit Cooperative Research Program
TRB	Transportation Research Board
U.S.DOT	United States Department of Transportation