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Transit and Urban Form

COMMUTER AND LIGHT RAIL TRANSIT CORRIDORS: THE LAND USE CONNECTION

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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, Public Policy and Transit Oriented Development: Six International Case Studies.

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 generalized direct transit demand estimation method 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

[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

	Light Rail (N = 261)				Commuter Rail (N = 526)			
Continuous Variables	**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

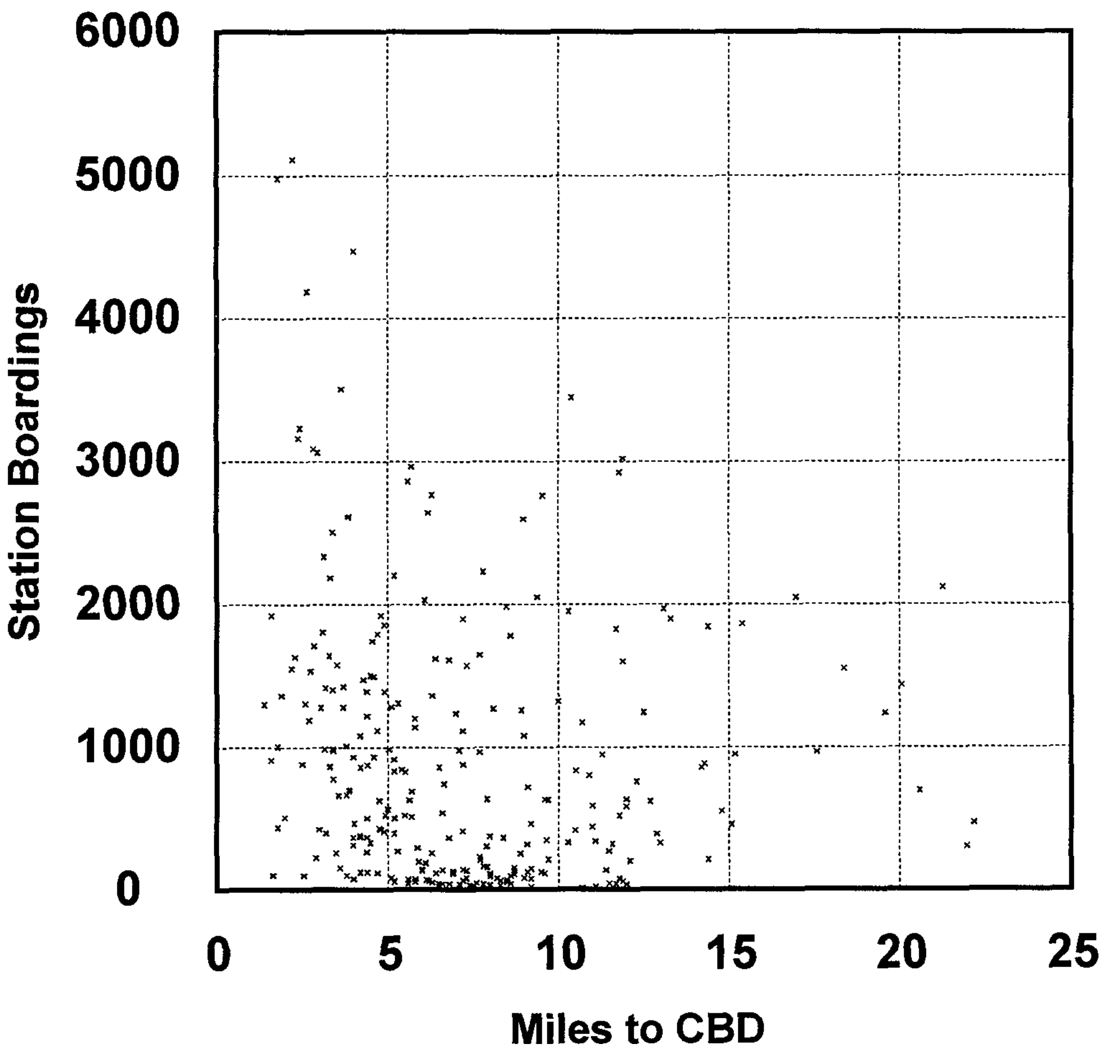


**Figure 2.
Commuter Rail Station Boardings
by Distance to the CBD**

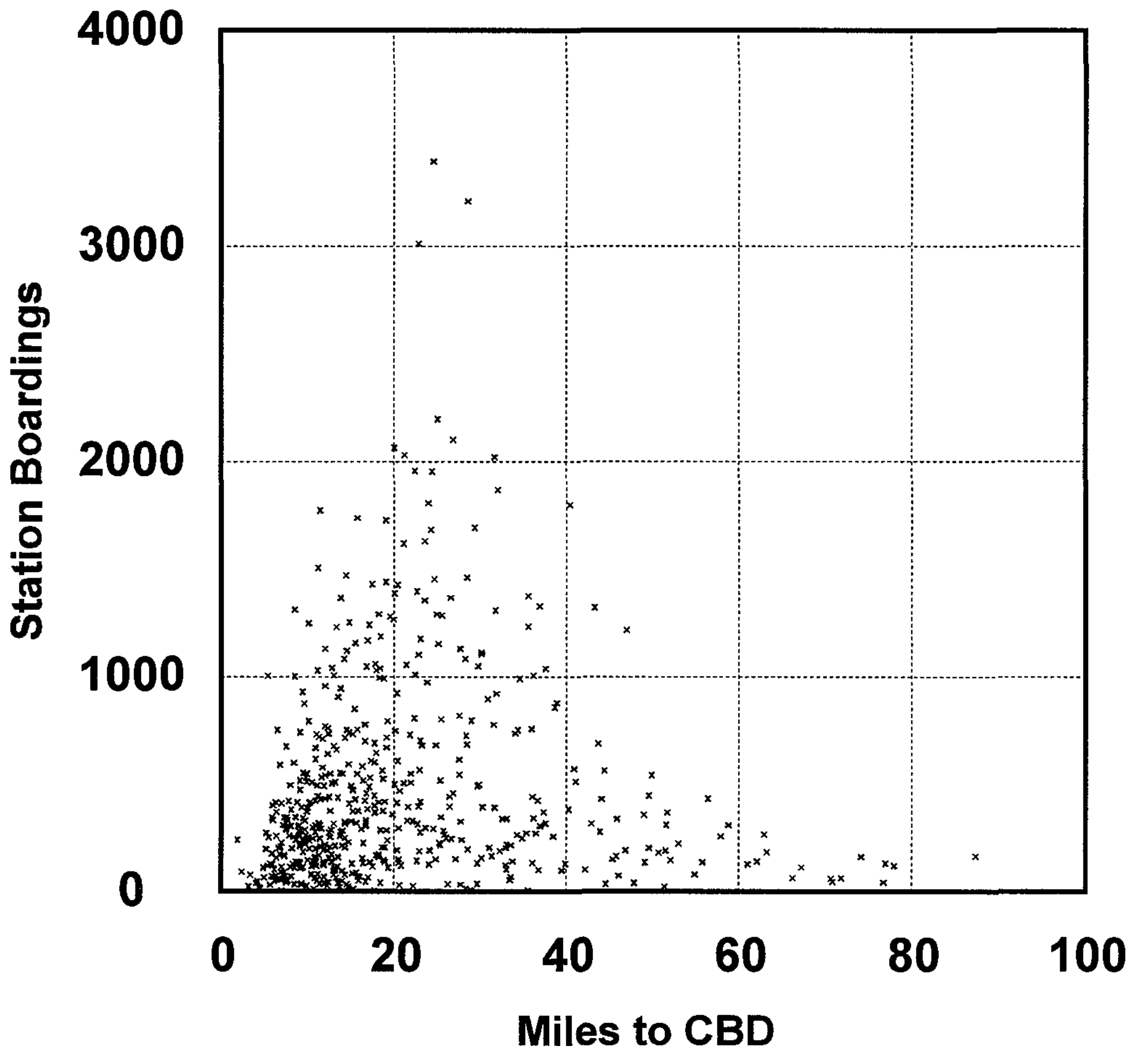


Table 6. Simple Correlation Coefficient Matrix Light Rail
(All variables converted to natural logarithms except dummy variables)

	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.

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

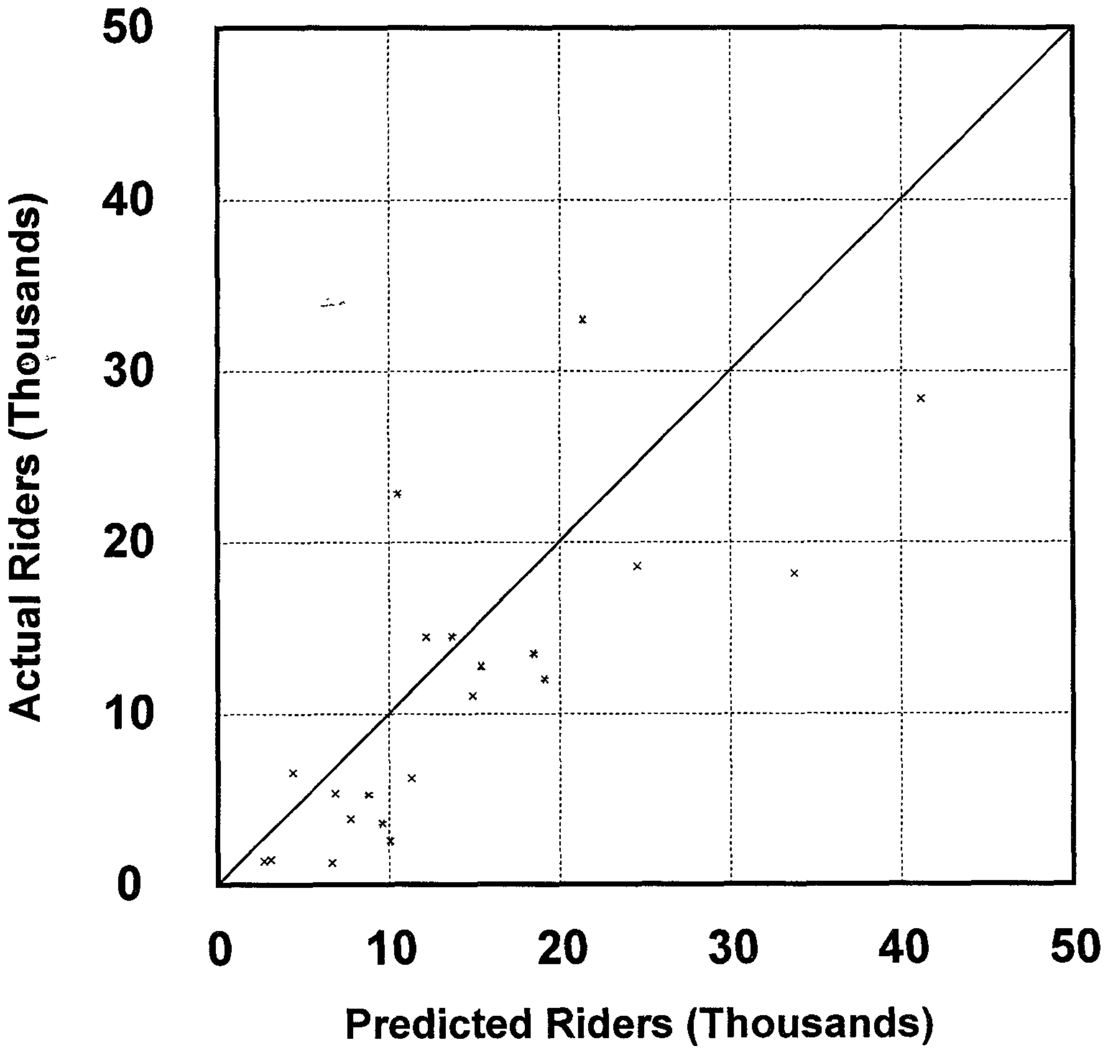


Figure 4.
Predicted Versus Actual Ridership by Commuter Rail Line

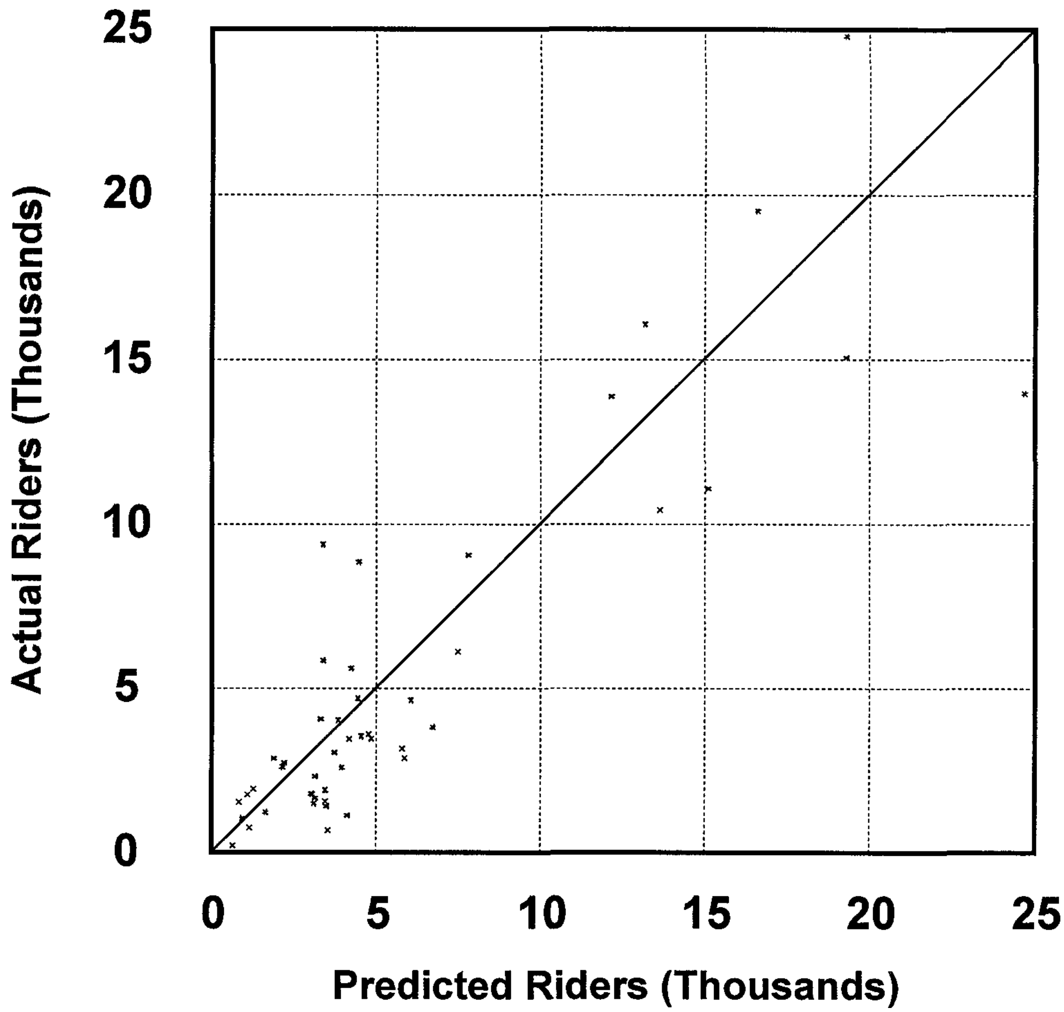


Table 11. Station Boarding Sensitivities

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

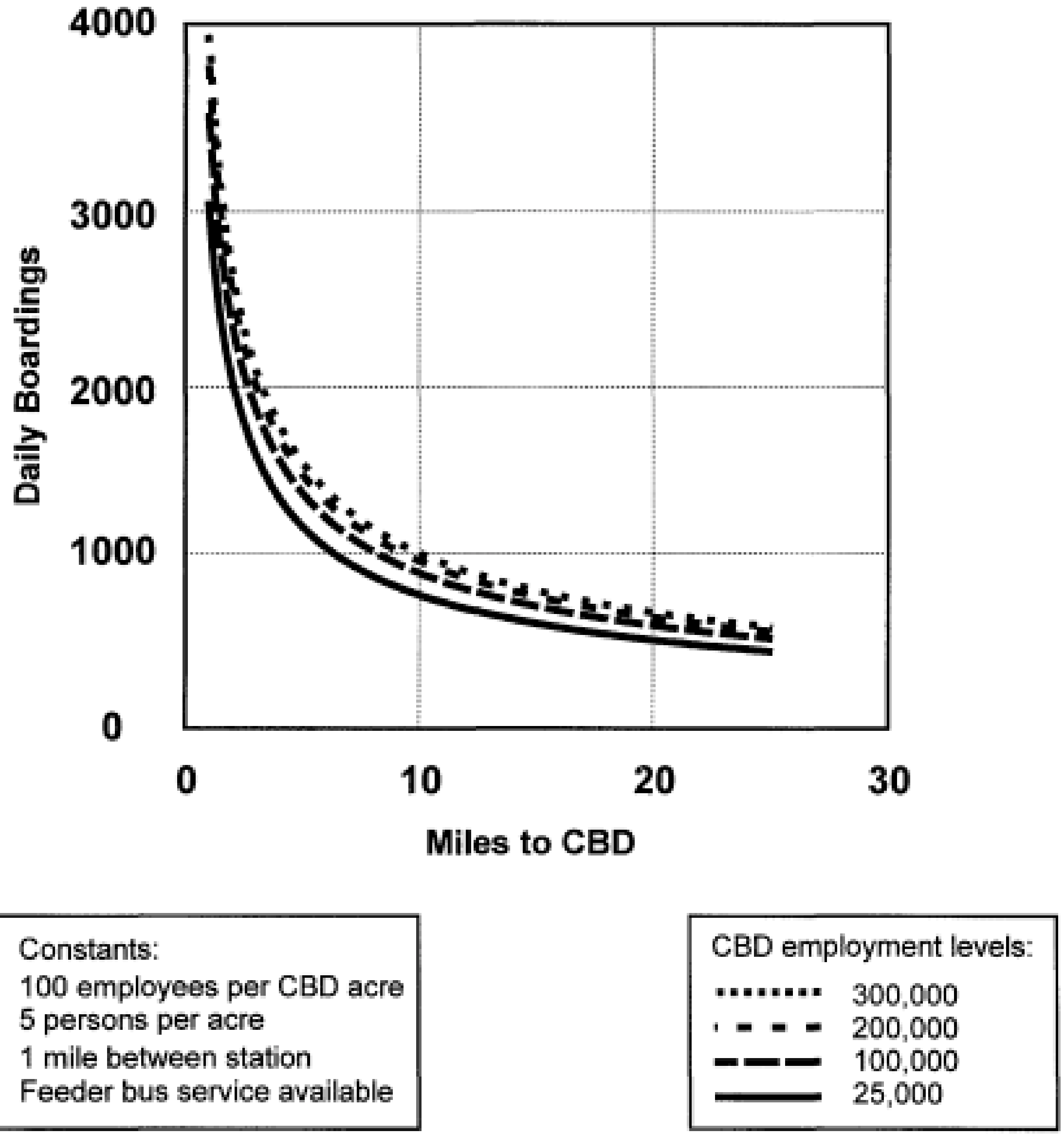


Figure 6.
Light Rail Station Boardings
by Distance to the CBD
and CBD Employment Density

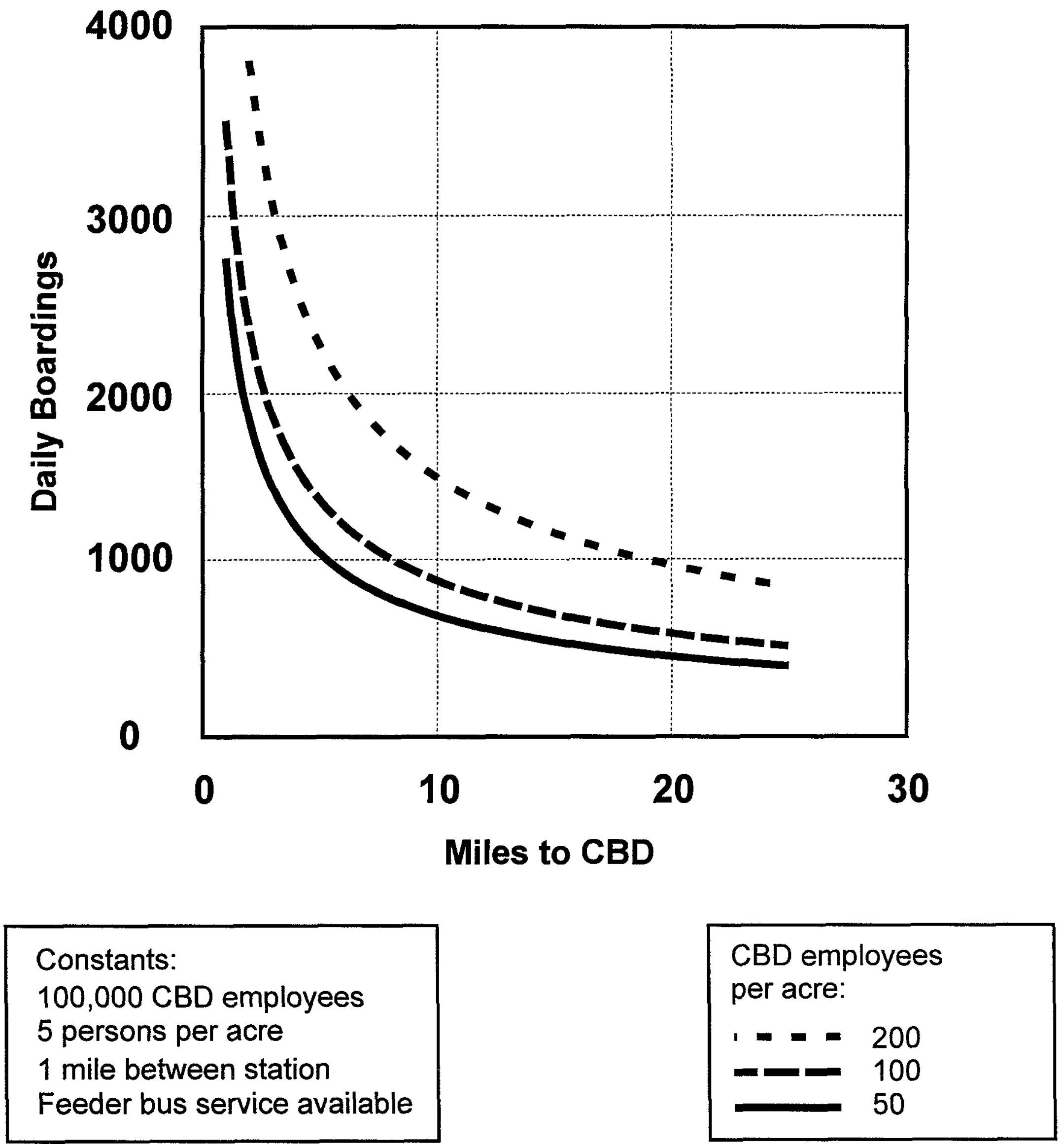


Figure 7.
Light Rail Station Boardings by Distance to the CBD and Residential Density

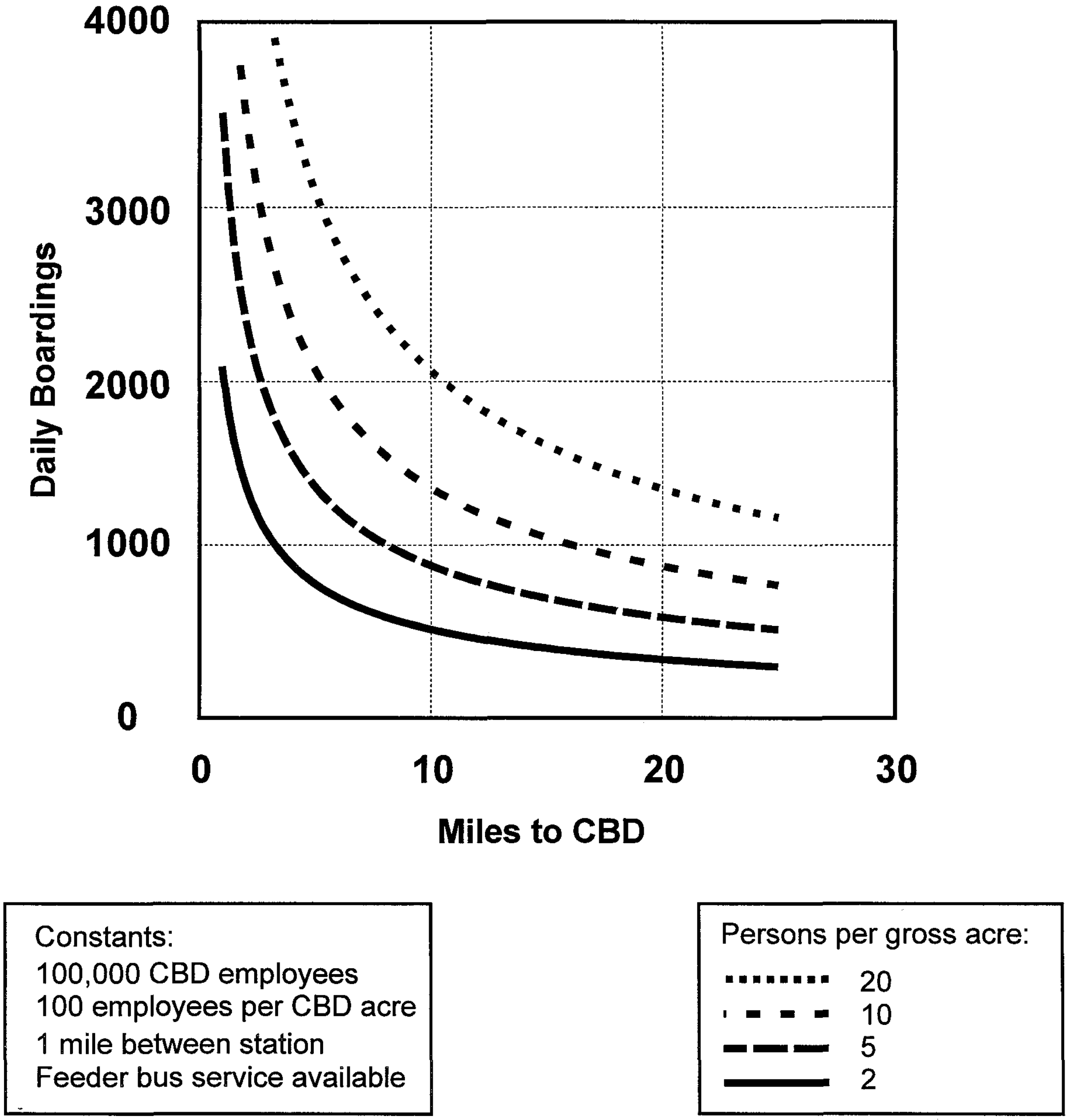
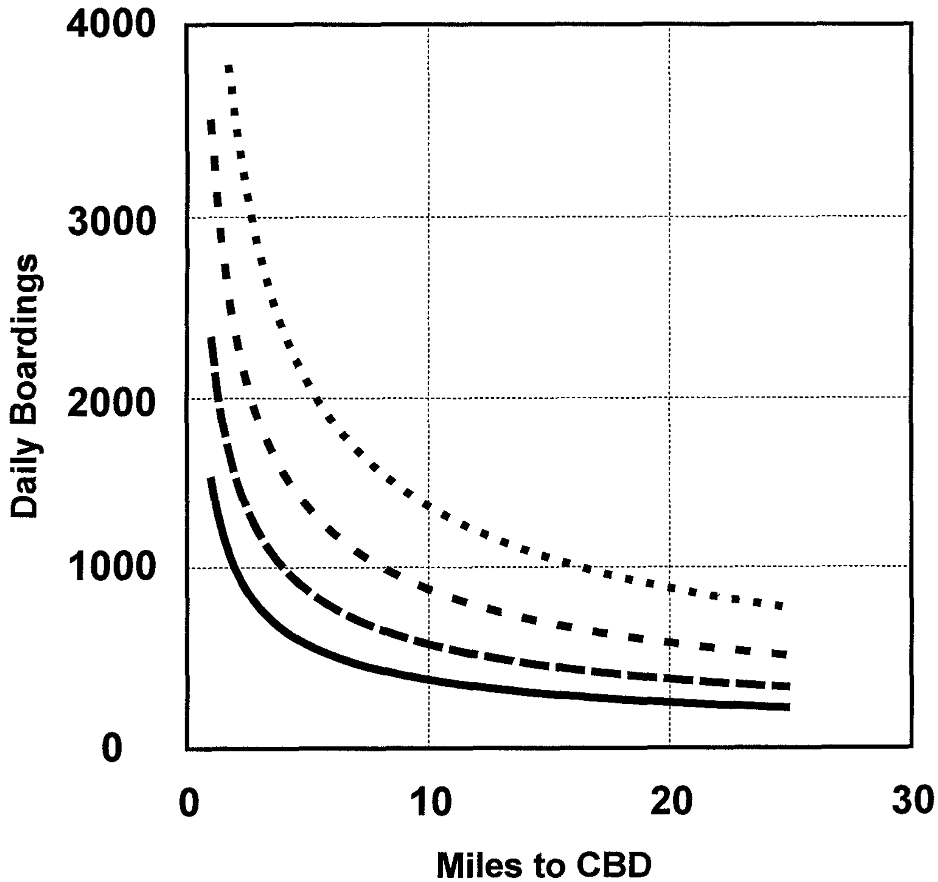


Figure 8.
Light Rail Station Boardings by Distance to the CBD and Access Modes



Constants:
100,000 CBD employees
100 employees per CBD acre
5 persons per acre
1 mile between station

Access modes:
Bus & parking
Bus emphasis
Parking emphasis
No bus or parking

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

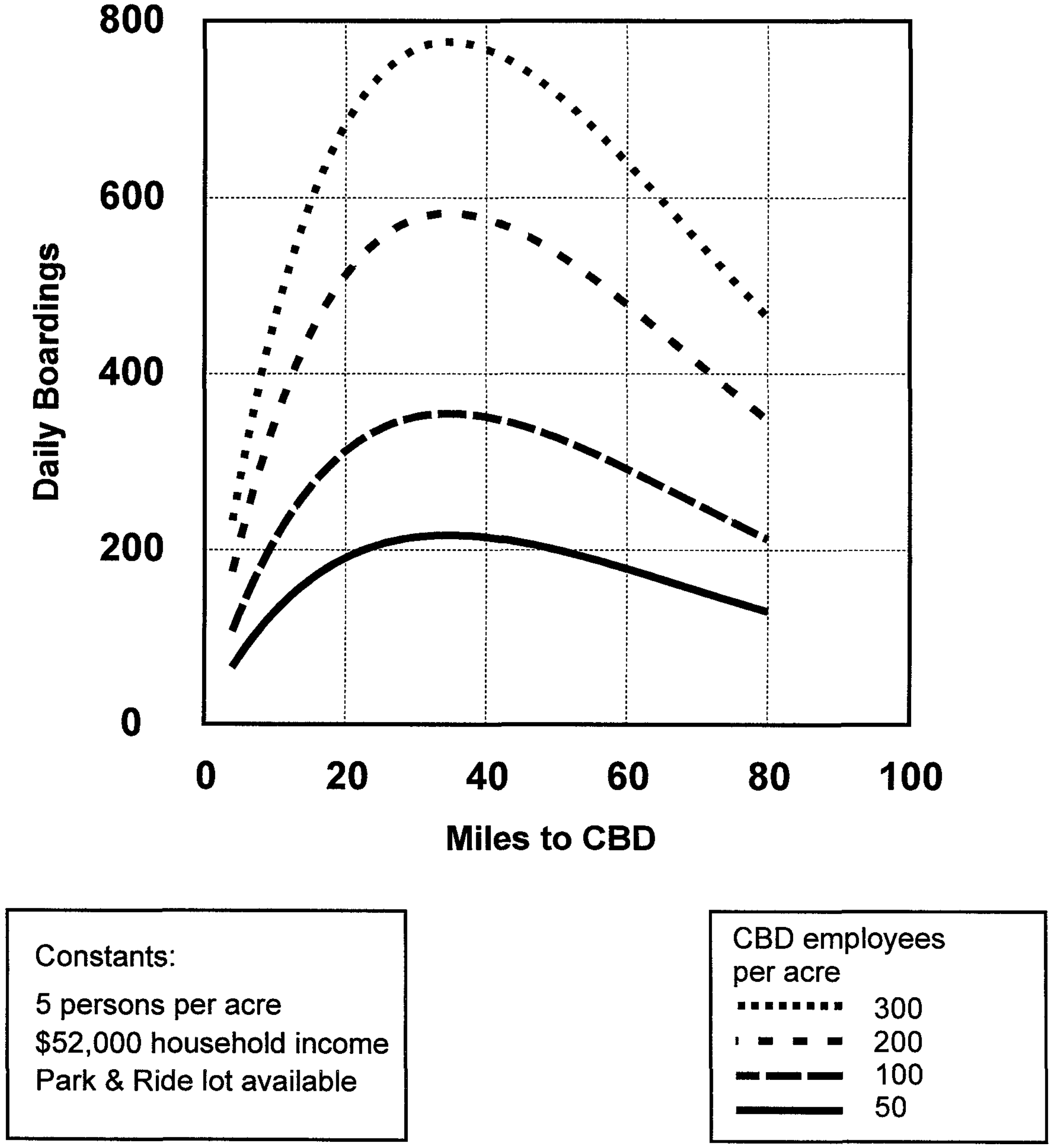


**Figure 10.
Commuter Rail Station Boardings
by Distance to the CBD
and Residential Density**

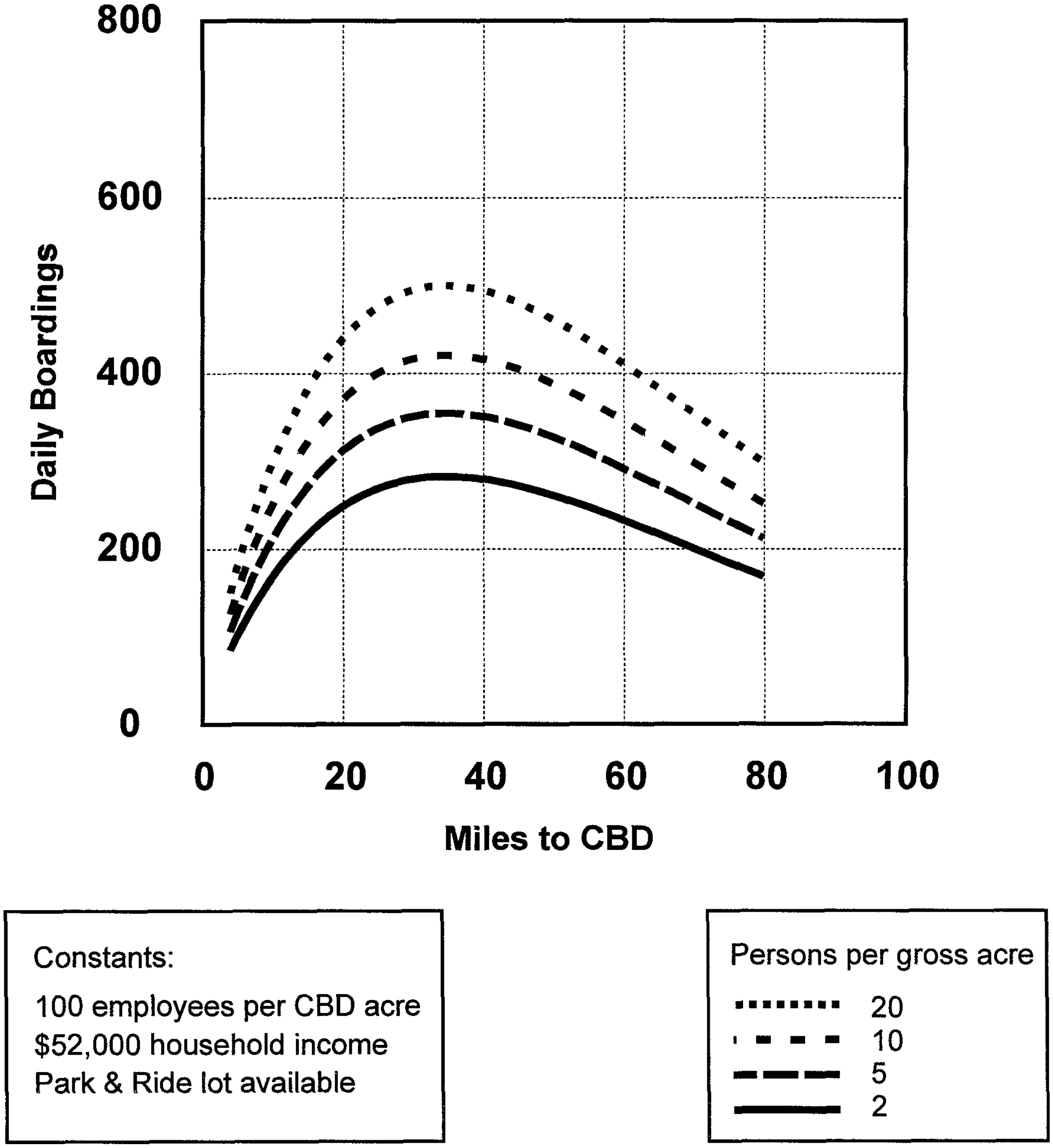


Figure 11.
Commuter Rail Station Boardings by Distance to the CBD and Household Income

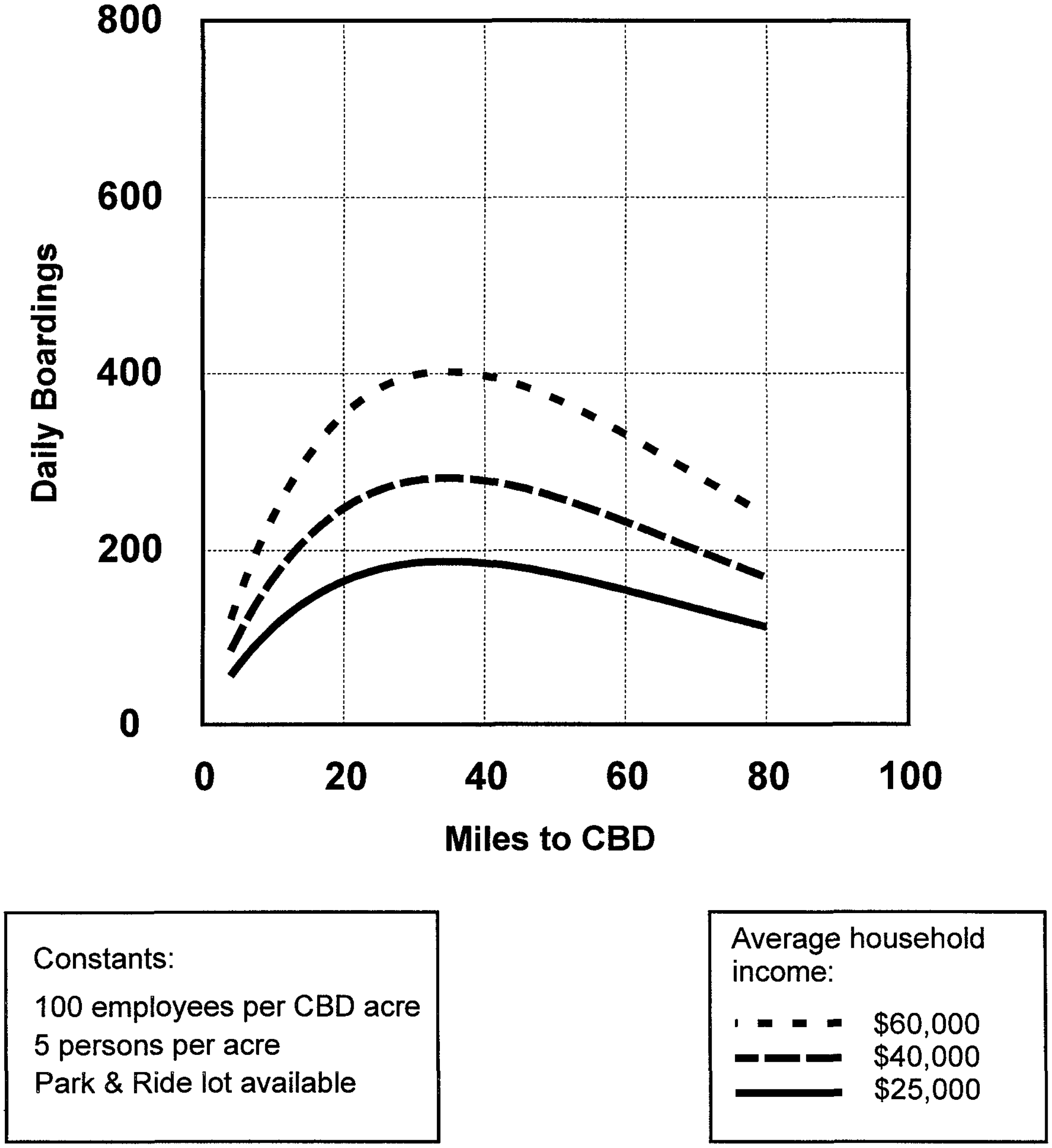


**Figure 12.
Commuter Rail Station Boardings
by Distance to the CBD
and Access Modes**