

## **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:

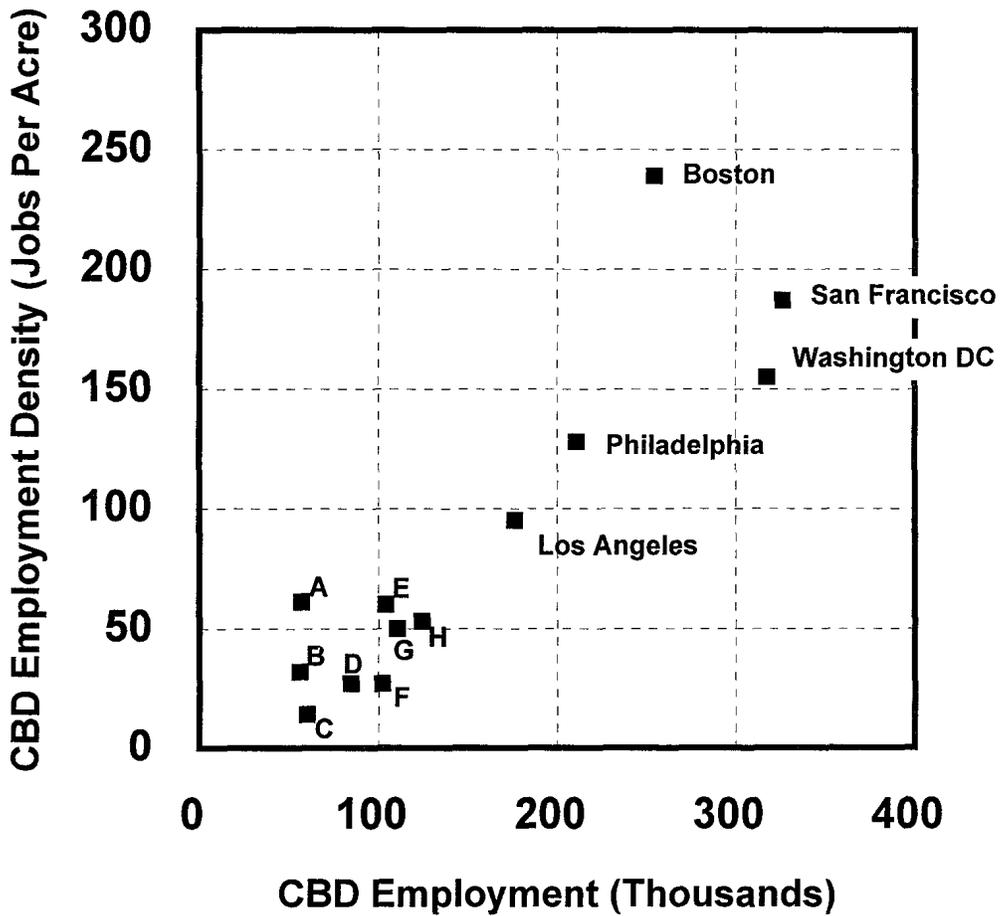
- CBD employment size
- population density (within two miles of station) gradient as a function of station distance from the CBD
- line length (with assumption of station spacing determining the number of stations)
- proportion of stations with substantial parking
- proportion of stations with bus feeders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

Note:

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

## ***TCRP H-1: Commuter and Light Rail Transit Corridors: The Land Use Connection***

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.

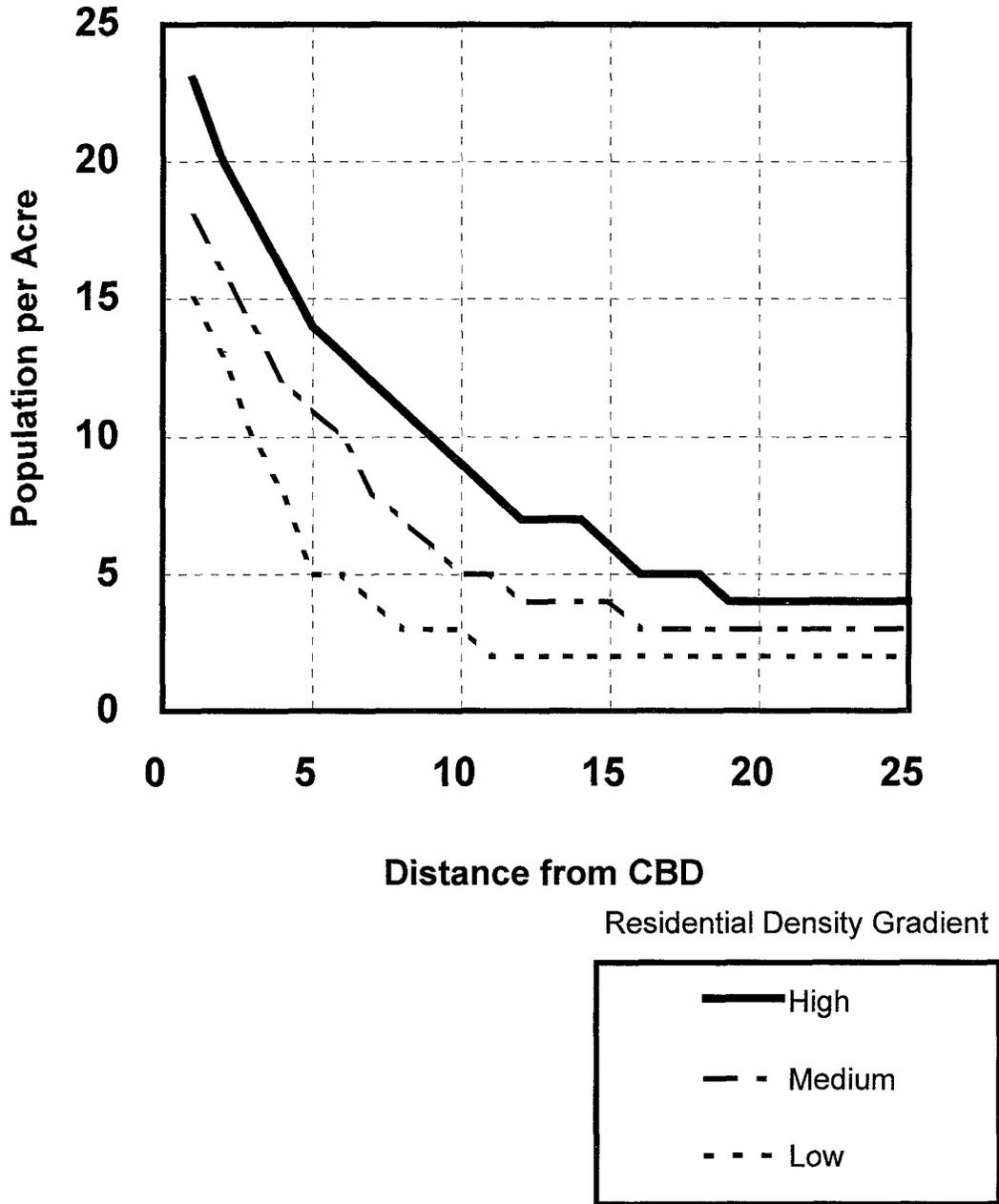
For the commuter rail gradients the high and medium gradients of the light rail line were used, but a very high gradient was added to account for the very high densities found near the CBDs of the largest cities. Also tested was a shallow density gradient to account for large cities, particularly in 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.

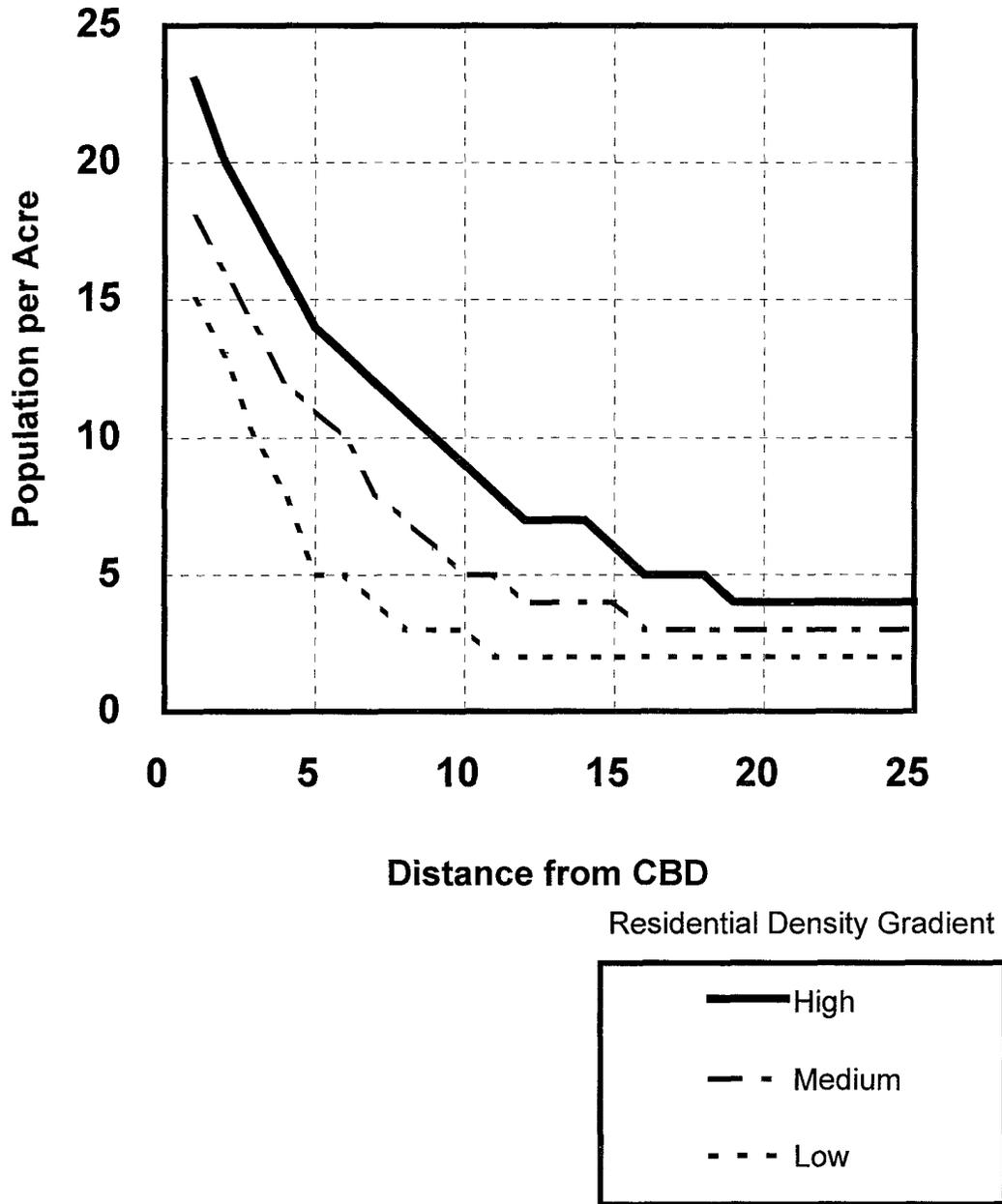
Measures per net residential acre subtract the amount of land in parks, streets and other right-of-ways, and non-residential uses from the number of developed acres. A 1992 Planners Advisory Service Memo on land use ratios indicates that, on average 50 percent of the developed land in cities is residential. 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.

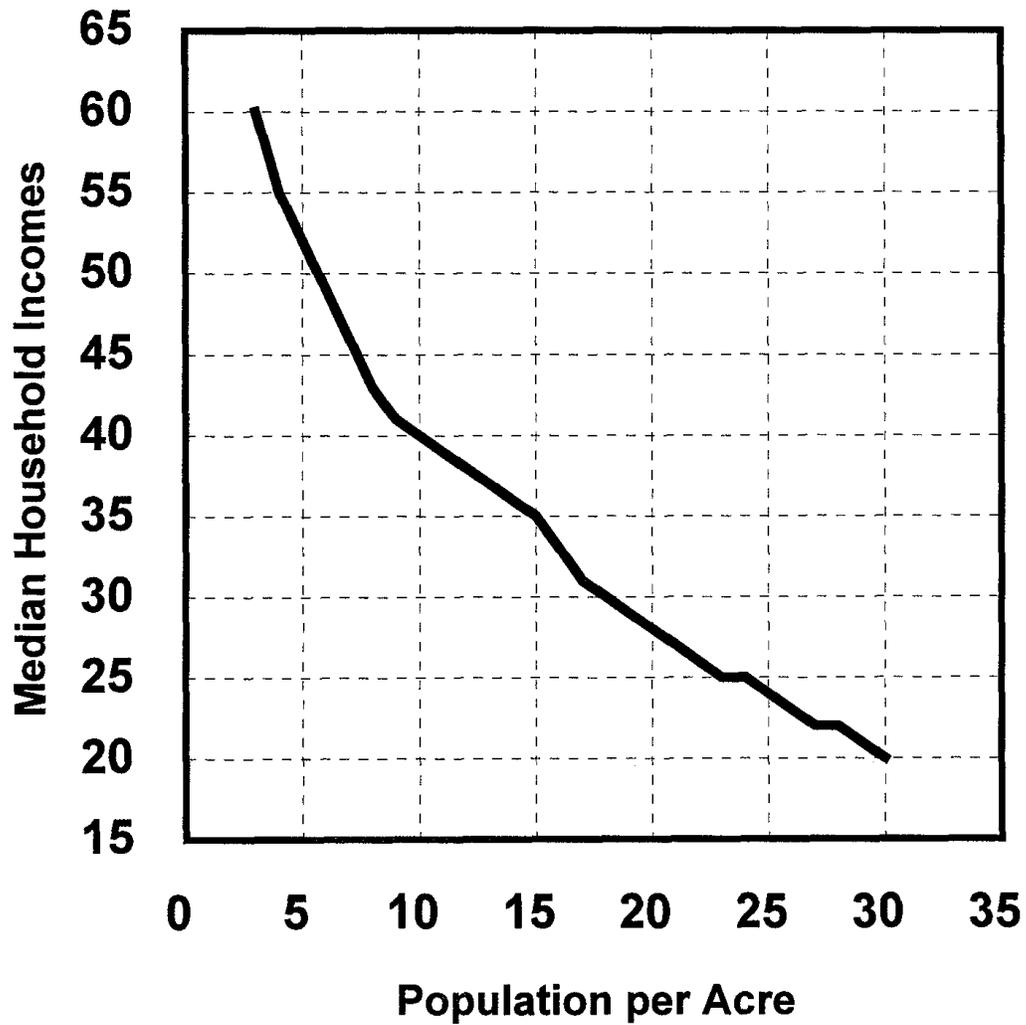
**Figure 14.**  
**Assumed Residential Density**  
**Gradients:**  
**Hypothetical Light Rail Corridors**



**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**

<u>Light Rail</u>		
<b>Distance Range</b>	<b>Percent Feeder Bus</b>	<b>Percent Parking Available</b>
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

<u>Commuter Rail</u>		
<b>Distance Range</b>	<b>Percent Feeder Bus</b>	<b>Percent Parking Available</b>
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.

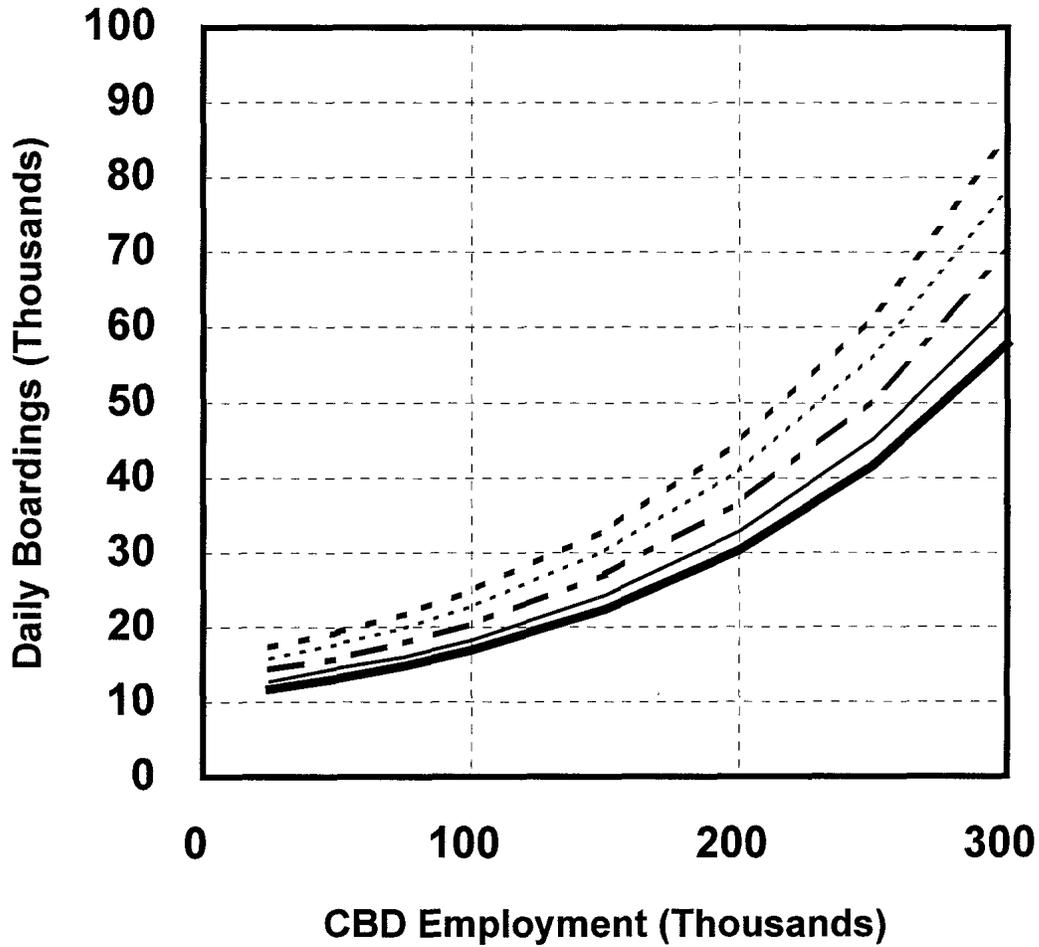
The impact of CBD employment density is isolated in Figure 18. With all else held constant (line length, access characteristics) the two square mile CBD (high employment density) and the three square mile CBD (low employment density) are compared. At the lower CBD employment levels there is hardly any 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**

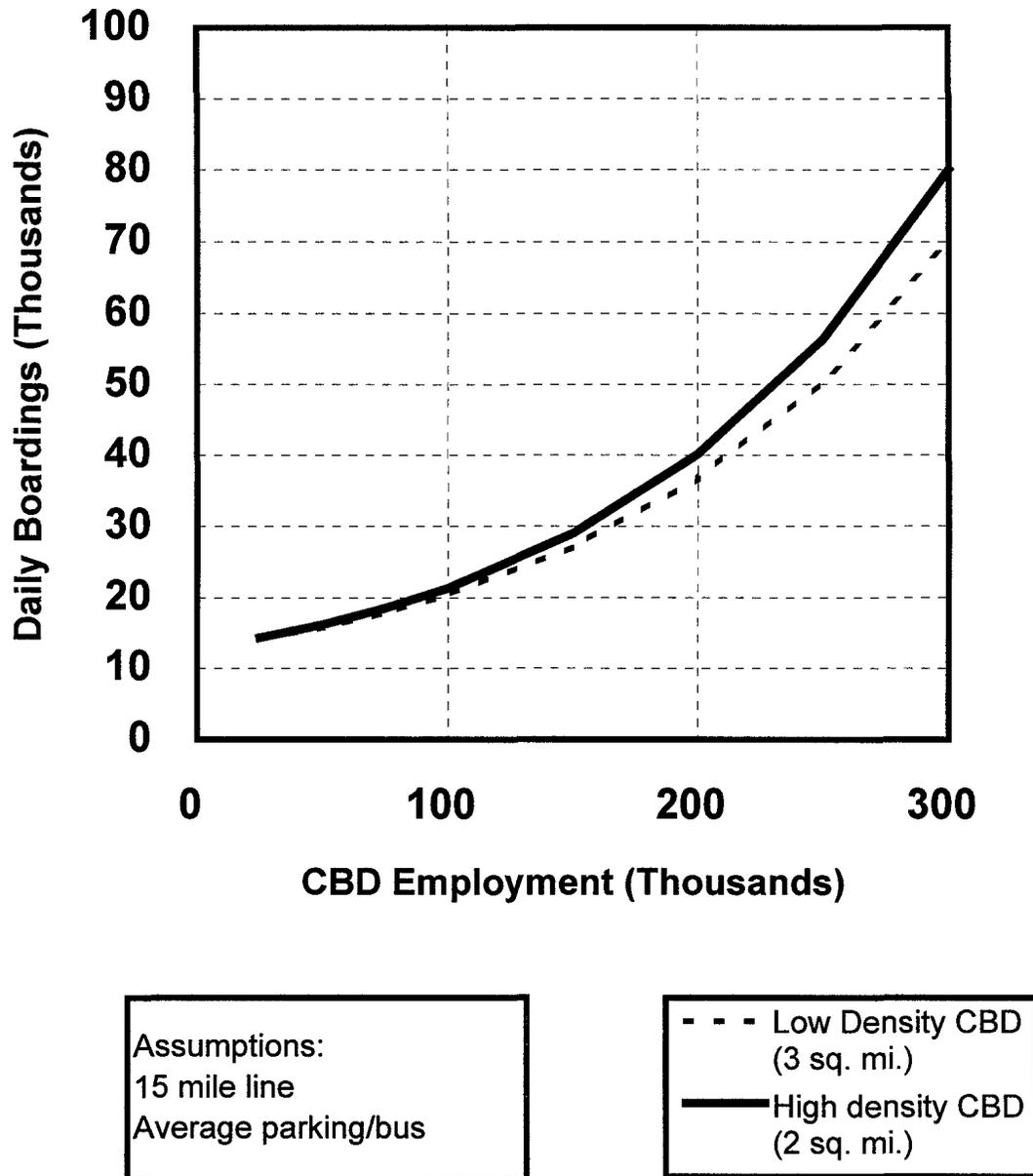


Assumptions:  
 Low density CBD (3 sq. mi.)\*  
 Low residential density gradient  
 Average parking/bus

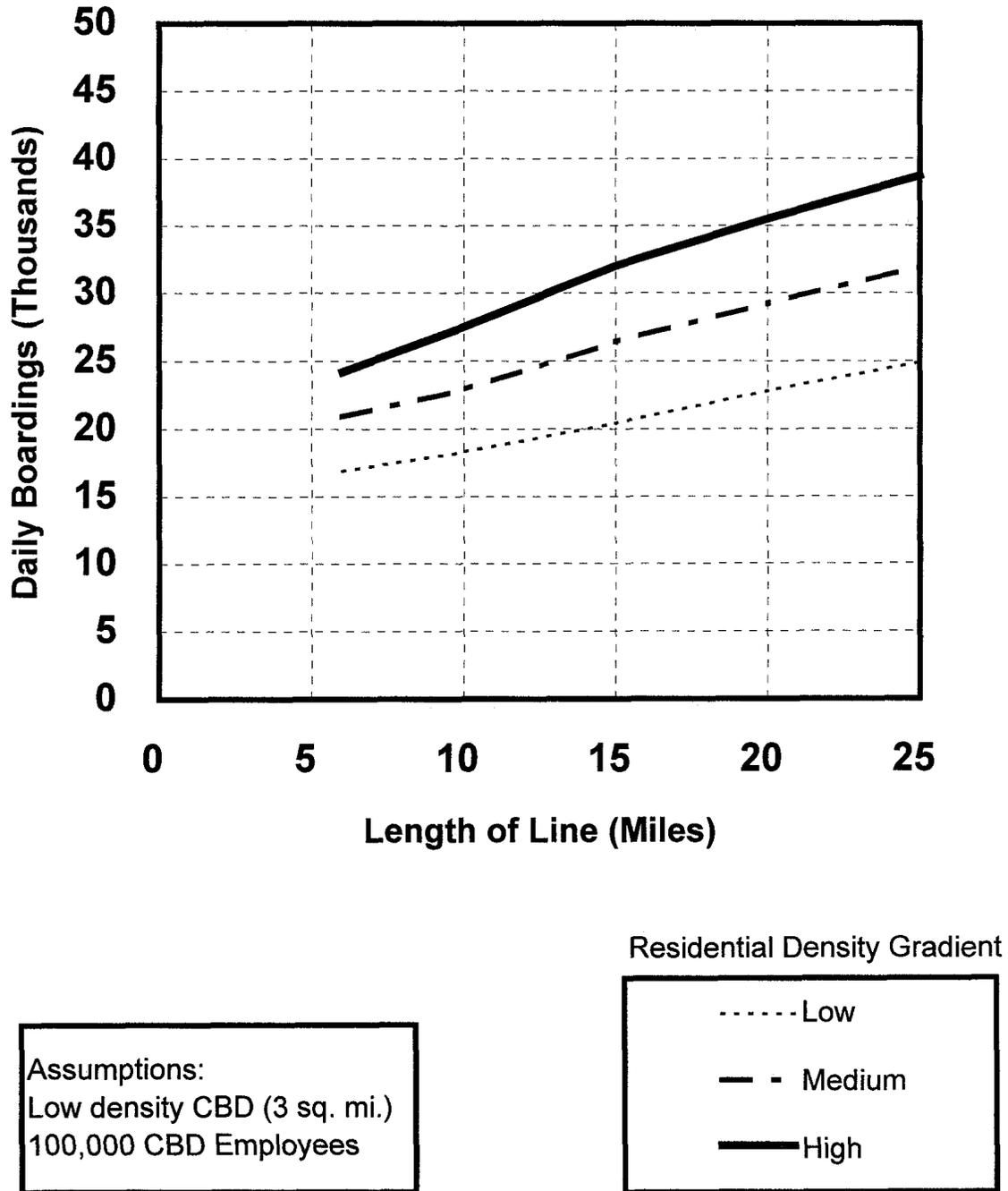
— 6-mile line  
 - - - 10-mile line  
 - · - · 15-mile line  
 ····· 20-mile line  
 - · - · 25-mile line

\*Note:  
 CBD density varies with CBD  
 employment size.

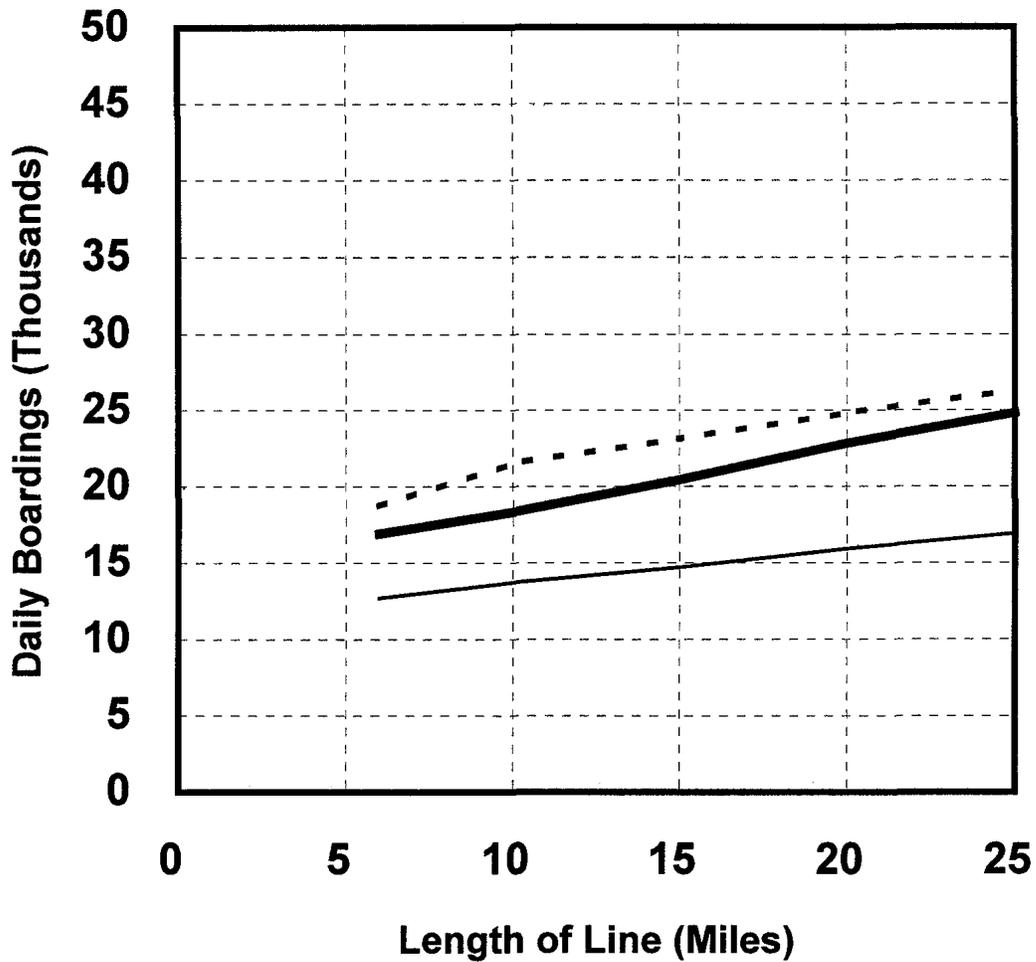
**Figure 18.**  
**Light Rail Daily Riders**  
**by CBD Jobs and CBD Size**



**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**



**Assumptions:**  
 Low density CBD (3 sq. mi.)  
 100,000 CBD Employees  
 Low residential density gradient

**Access Modes**  
 — Average park/bus  
 — More park, less bus  
 - - - More bus, less park

## **Commuter Rail**

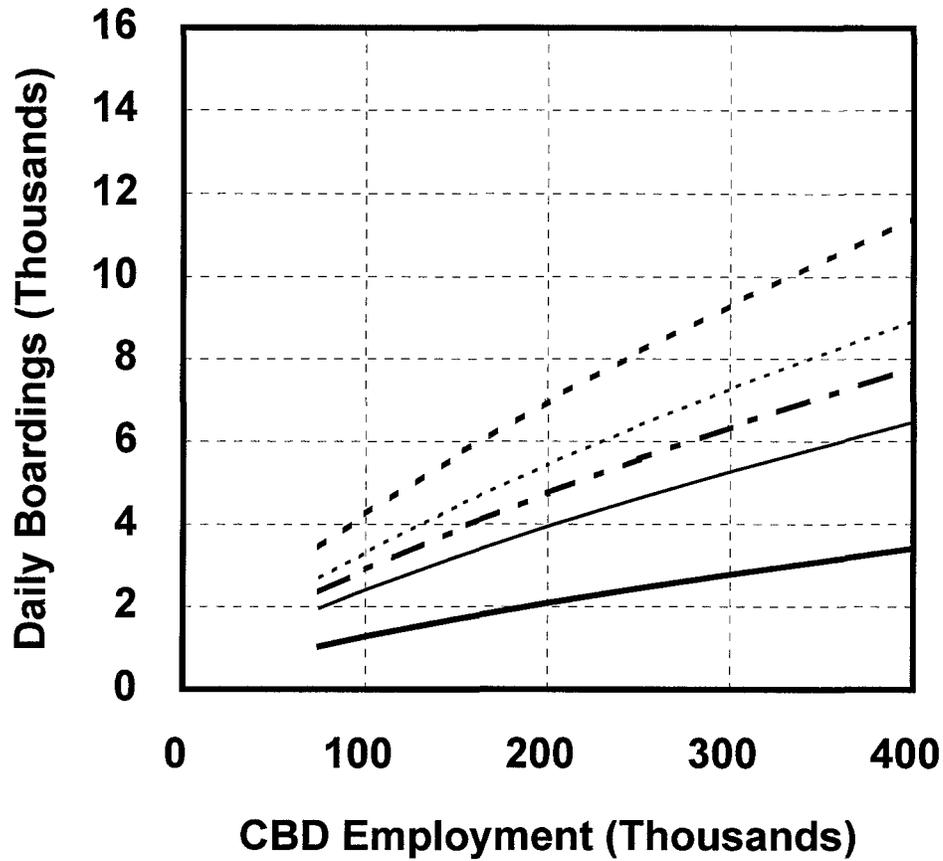
In Figure 21 and Figure 22 daily riders are plotted against the employment size for the five commuter rail line lengths tested, with Figure 21 showing the results for low employment density CBDs and Figure 22 showing them for high density CBD ridership. As expected, ridership rises significantly with 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)**

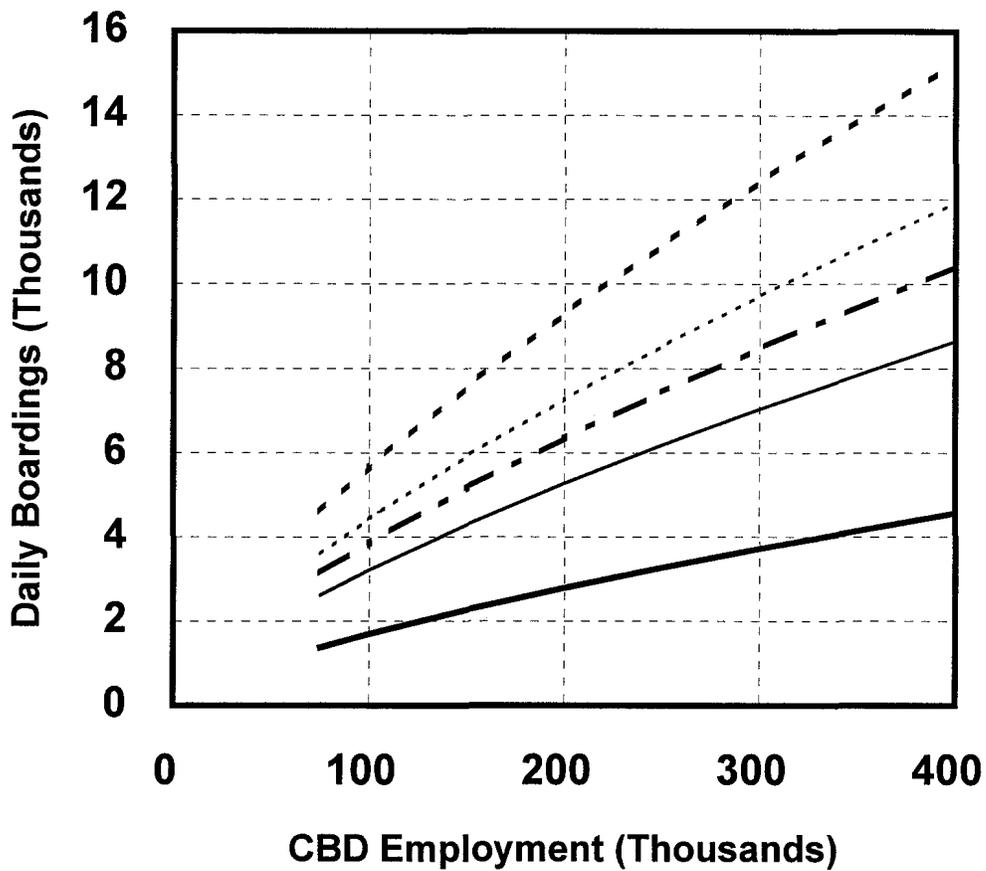


**Assumptions:**  
 High residential density gradient  
 Average parking/bus  
 Low density CBD (3 sq. mi.)\*

— 20-mile line  
 - - - 30-mile line  
 - - - 40-mile line  
 ..... 50-mile line  
 - . - . 80-mile line

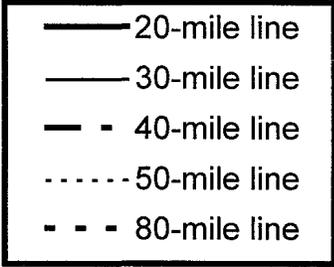
\*Note:  
 CBD density varies with CBD  
 employment size.

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

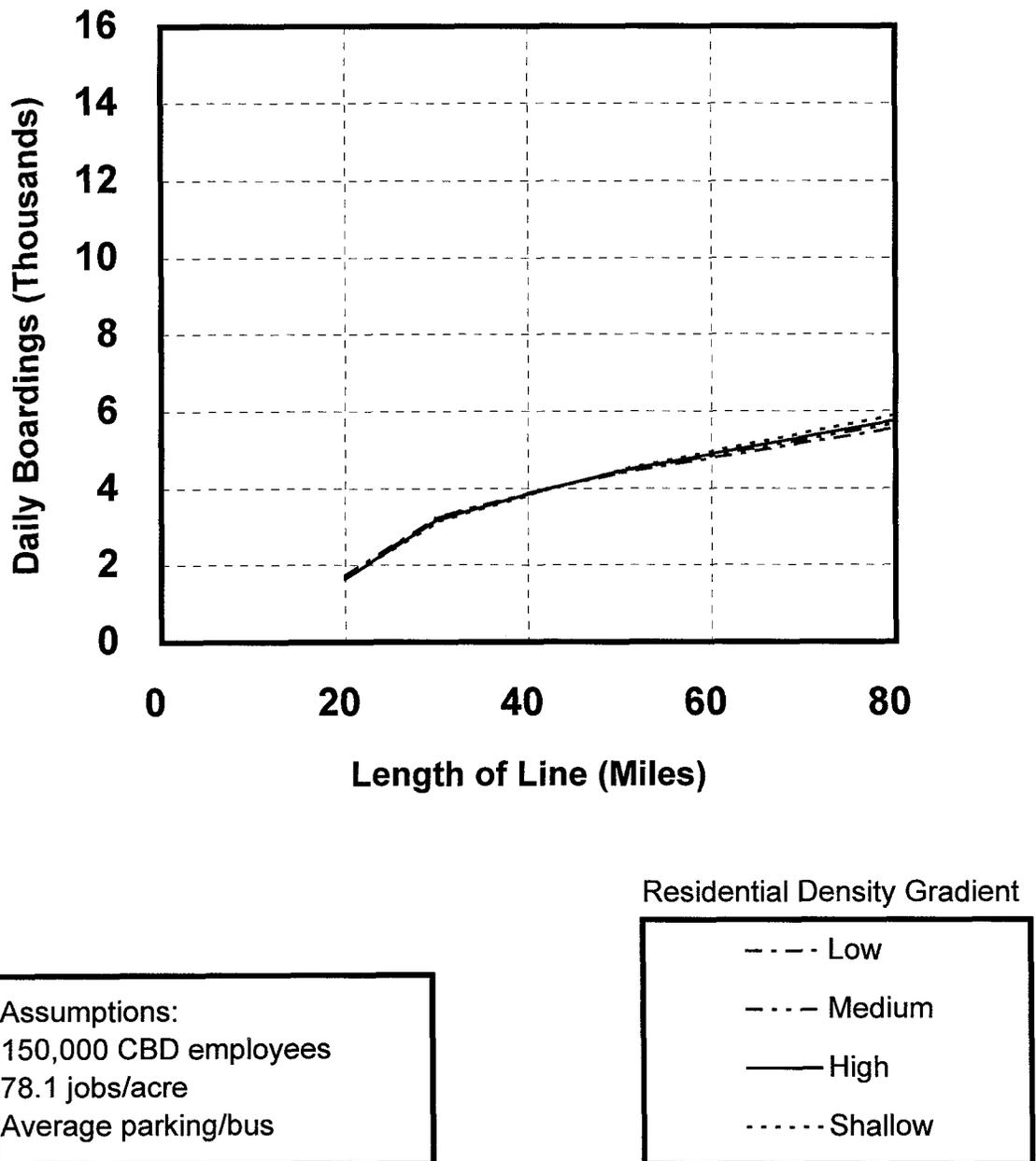


**Assumptions:**  
 High residential density gradient  
 Average parking/bus  
 High density CBD (2 sq. mi.)\*

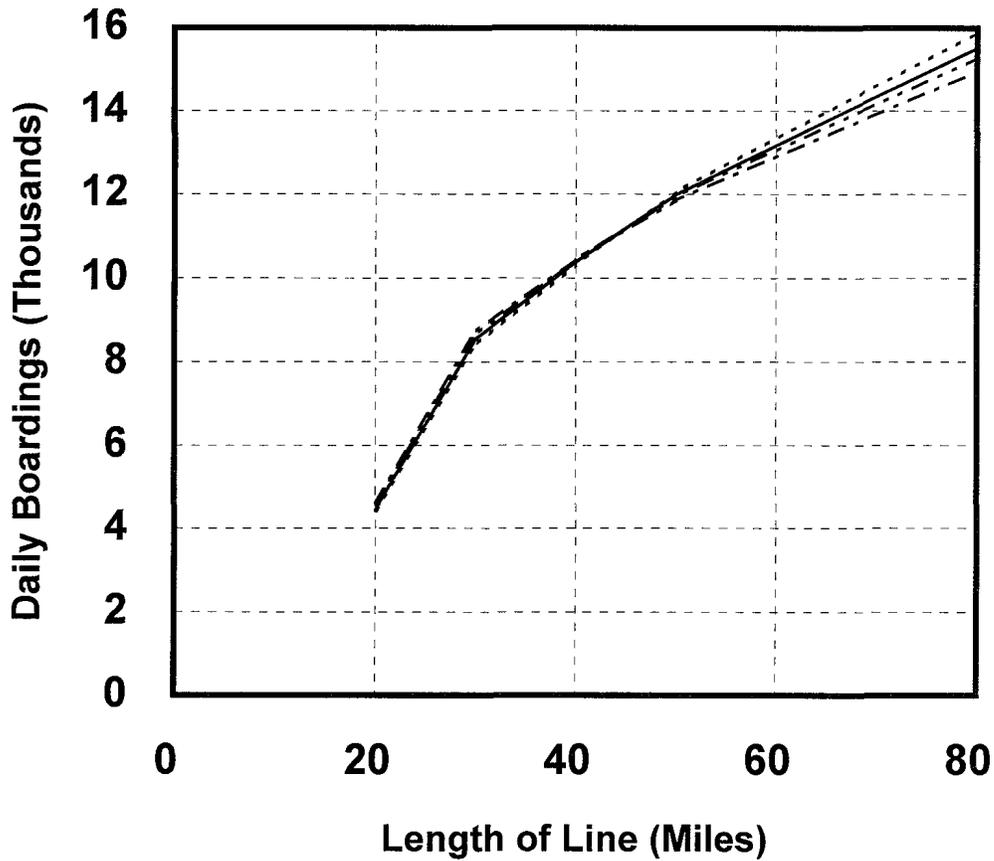
\*Note:  
 CBD density varies with CBD  
 employment size.



**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)**



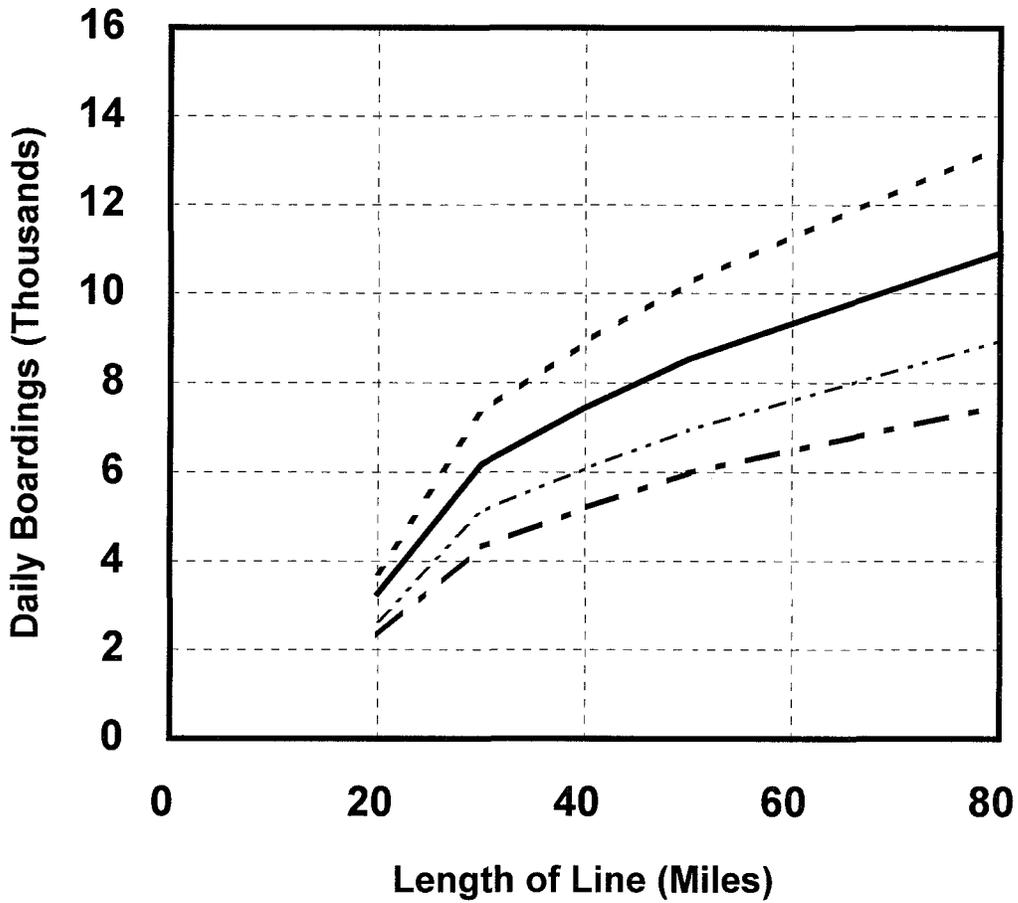
Assumptions:  
400,000 CBD employees  
312.5 jobs/acre  
Average parking/bus

Residential Density Gradient

- Low
- . - . - Medium
- High
- ..... Shallow

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

Access Modes

- Average park/bus
- - - More bus
- · - Less Parking
- · · - More bus, less park

## 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:

$$\text{Non-labor cost (\$ million)} = 1.342 + (1.441 \times \text{annual revenue vehicle-miles (millions)})$$

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

$$\text{Transit O\&M Labor Costs (1993 \$)} = \$66,004 \times \text{Total Light Rail O\&M Labor Requirements}$$

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**

System Characteristic	Vehicle Oper.	Labor Cost Component		
		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 =  
 $1.41 \times (6,440 \times \text{track-miles}$   
 $+ 1,220 \times \text{number of stations}$   
 $+ 1,920 \times \text{vehicles in fleet})$

Capital costs (in 000s of 1993 \$) for light rail =

$$\begin{aligned} & 1.41 \times (2940 \times \text{track-miles}) \\ & + 2,350 \times \text{at-grade track-miles} \\ & + 6,250 \times \text{elevated track-miles} \\ & + 25,680 \times \text{subway track-miles} \\ & + 160 \times \text{number of stations} \\ & + 890 \times \text{number of at-grade stations} \\ & + 5,440 \times \text{number of elevated stations} \\ & + 40,860 \times \text{number of subway stations} \\ & + 1,920 \times \text{number of vehicle in fleet} \end{aligned}$$

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 Urban Rail in America. 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:

$$\text{Vehicles in maximum service} = (\text{boardings} \times 0.22 \times \text{line length} \times 2) / (75 \times 17),$$

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  $\times$  the line length  $\times$  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, and 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:

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

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**

System Characteristic	Vehicle Oper.	Labor Cost Component		
		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 (  $-1.109 + 0.020 \times \text{track-miles} + 0.302 \times \text{annual vehicle-miles per track-miles}$ ) squared.

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

Summary Formula for Total Commuter Rail Transit O&M Labor Requirements:

$$1.25 \times \{ 30.542 + 1.351 \times \text{Annual Revenue Hours of Service (in 1,000a)} + 1.265 \times \text{Number of Vehicles in Fleet} + (-1.109 + 0.020 \times \text{Number of Track Miles} + 0.302 \times \text{Annual Revenue Miles (in 1000s) per Track Mile}) \}$$

Summary Formula for Total Commuter Transit O&M Labor Costs =

$$\$66,004 \times \text{Total Light Rail O\&M Labor Requirements}$$

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 =  $1.24 \times (2,787 \times \text{route-miles} + 1,843 \times \text{number of vehicles in fleet} + 7,510 \times \text{number of stations})$

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 =  $(\text{boardings} \times 0.30 \times \text{line length} \times 2) / (120 \times \text{speed})$ ,

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**

<i>Commuter Rail Capital Component</i>	<i>Unit of Measure</i>	<i>Unit Cost (1993 \$)</i>
<b>1 Trackwork Improvements</b>		
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
<b>2 Stations &amp; Parking</b>	Each	\$ 7,510,000
<b>3 CTC, Signals and Crossing Protection</b>		
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
<b>4 Site Improvements</b>		
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
<b>5 Maintenance and Storage Facilities (Incl. Layovers)</b>	Per Vehicle	\$ 430,000
<b>6 Right of Way</b>	Route Mile	\$ 150,000
<b>7 Rolling Stock</b>		
Locomotives	Each	\$ 1,660,000
Coaches – Single Level	Each	\$ 1,320,000
Coaches – Bi-Level	Each	\$ 1,770,000
<b>8 Agency Cost</b>		
(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)	
<b>System Average Cost</b>	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  $\times$  the line length  $\times$  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, and 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:

$$\text{Annual vehicle-miles} = [((\text{boardings} \times 0.30 \times \text{line length} \times 2) / 120)] \times 10 \times 295,$$

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, 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;

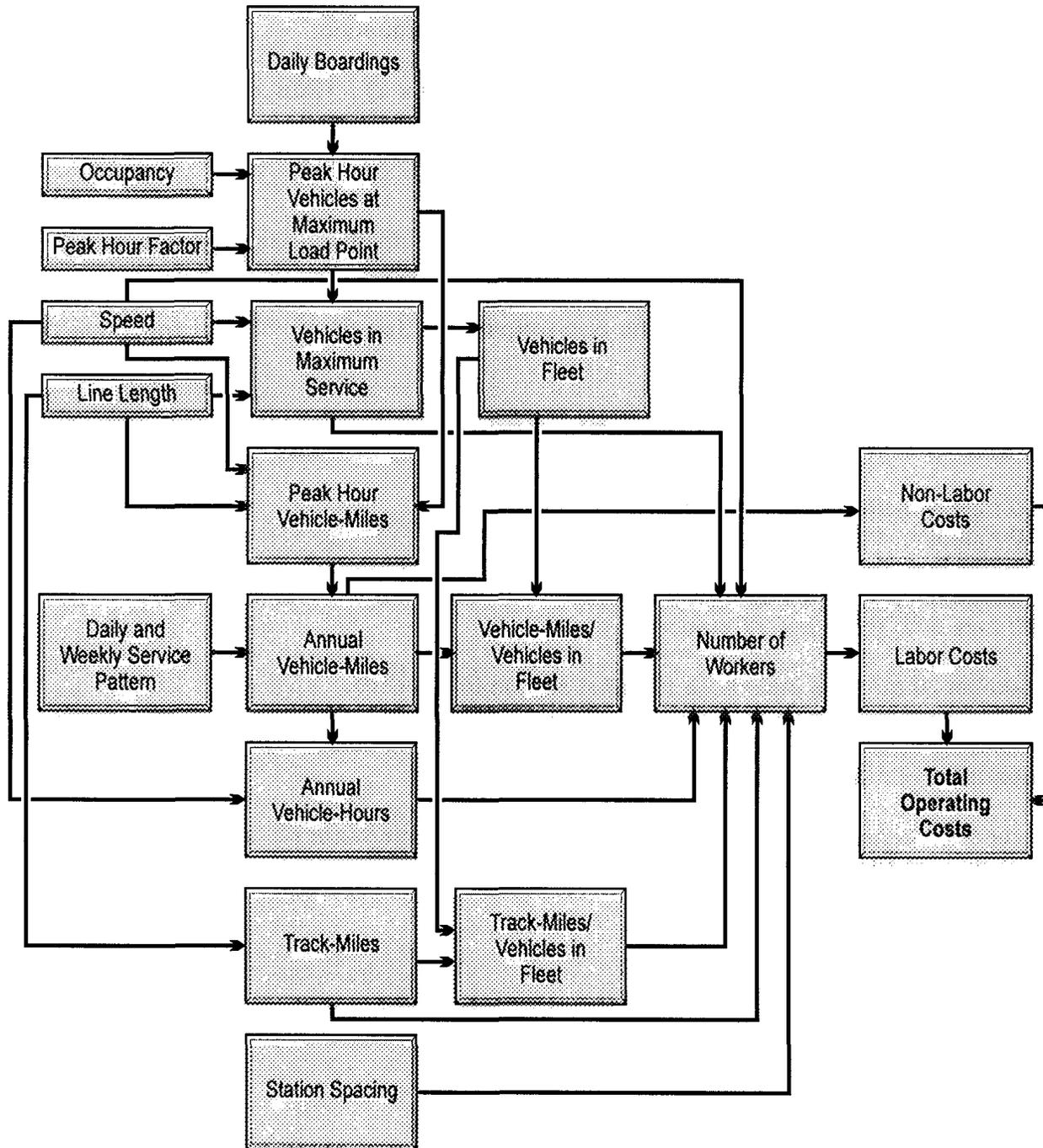
For 20-mile line, there are 9 stations;  
For 30-mile line, there are 14 stations;  
for 40-mile line, there are 19 stations;  
For 50-mile line, there are 21 stations; and  
For 80-mile line, there are 27 stations.

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

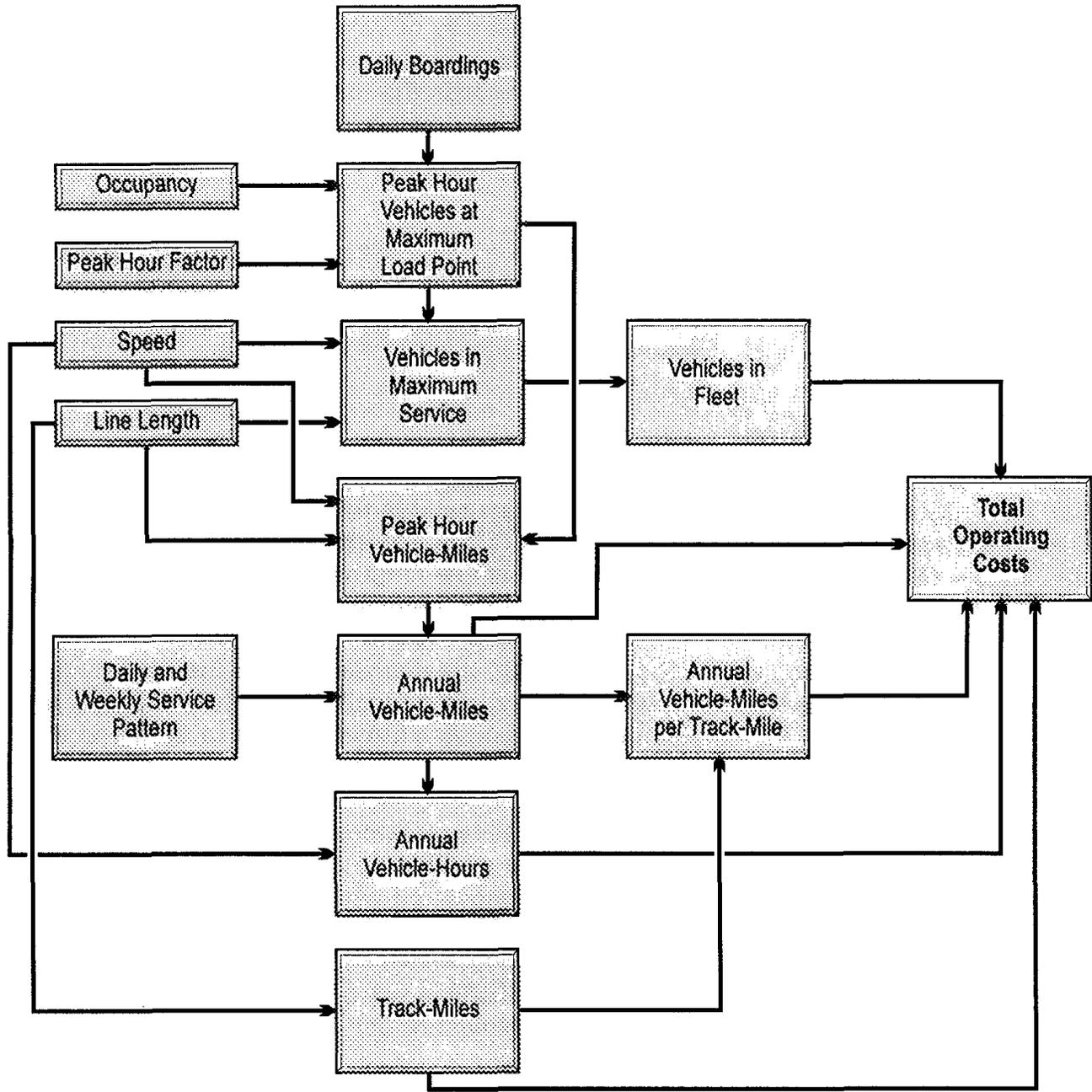
Once these values are calculated for each hypothetical commuter rail line, the operating and capital cost models can be applied directly.

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.

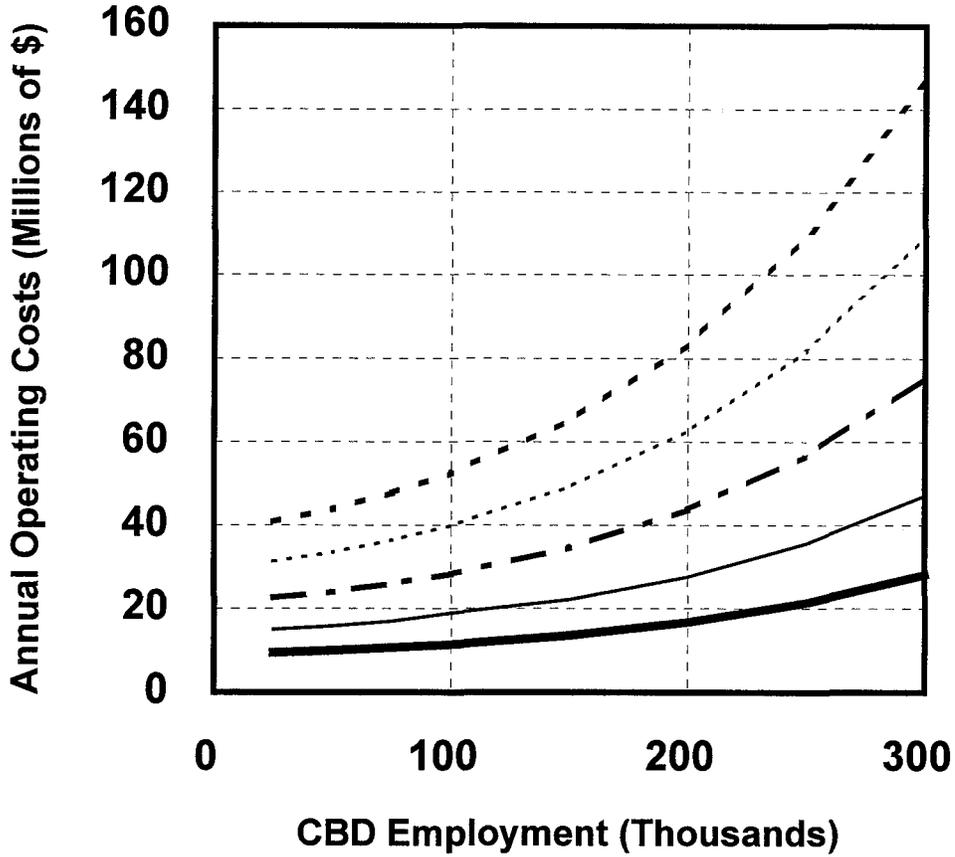
### **6.1 LIGHT RAIL COSTS**

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.

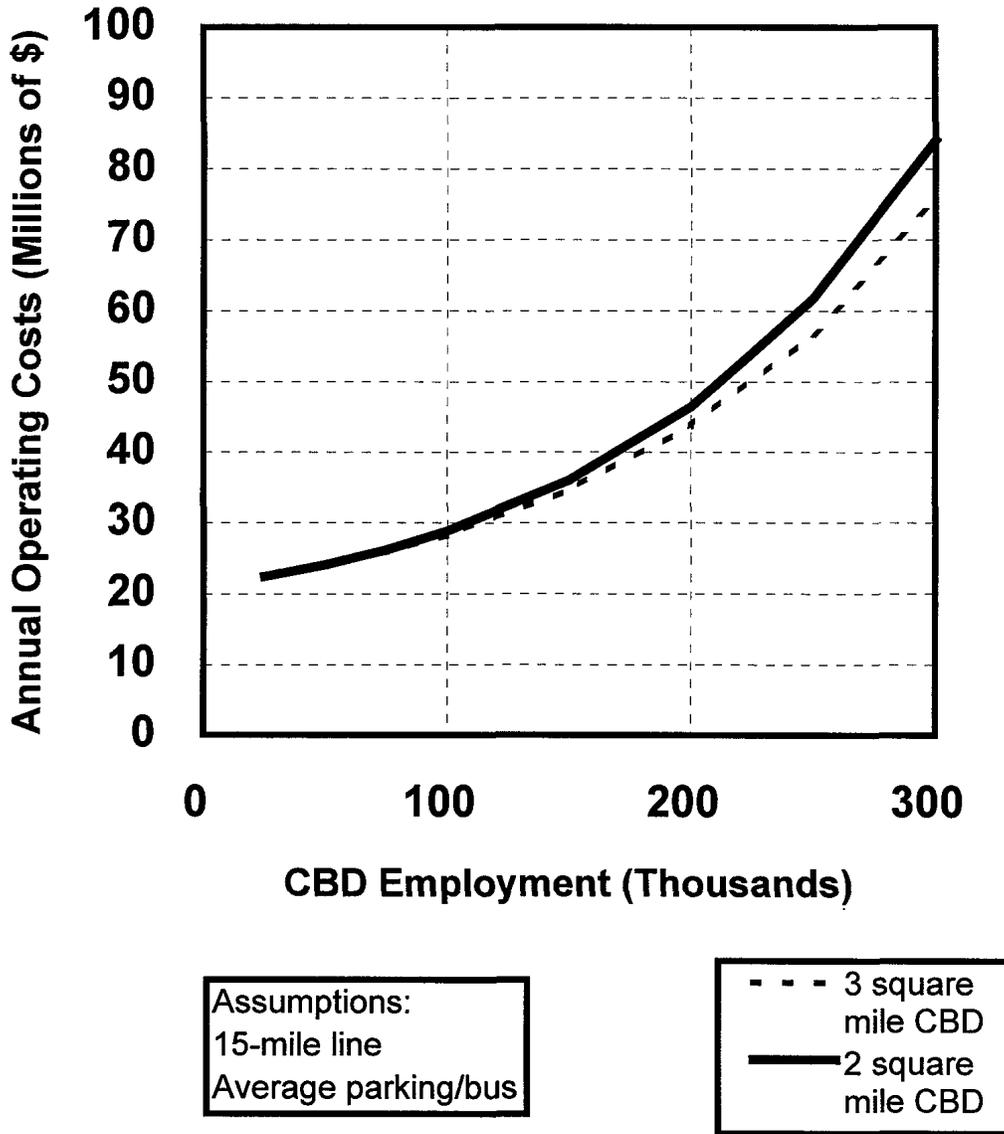
**Figure 28.**  
**Light Rail Operating Costs**  
**by CBD Jobs and Line Length**



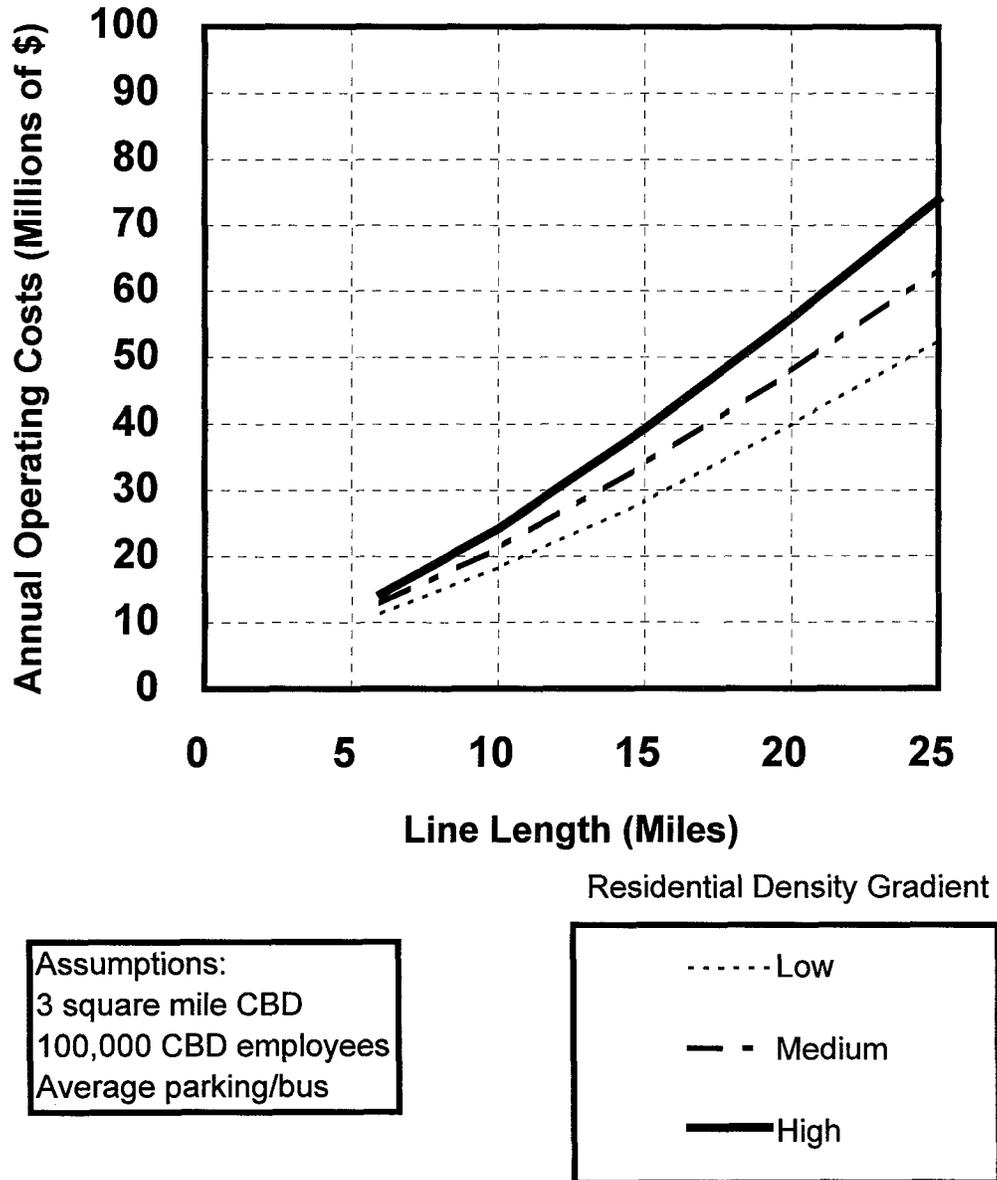
Assumptions:  
 3 square mile CBD  
 Low residential density gradient  
 Average parking/bus

- 6-mile line
- - - 10-mile line
- · - · 15-mile line
- · · · 20-mile line
- · - · 25-mile line

**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**

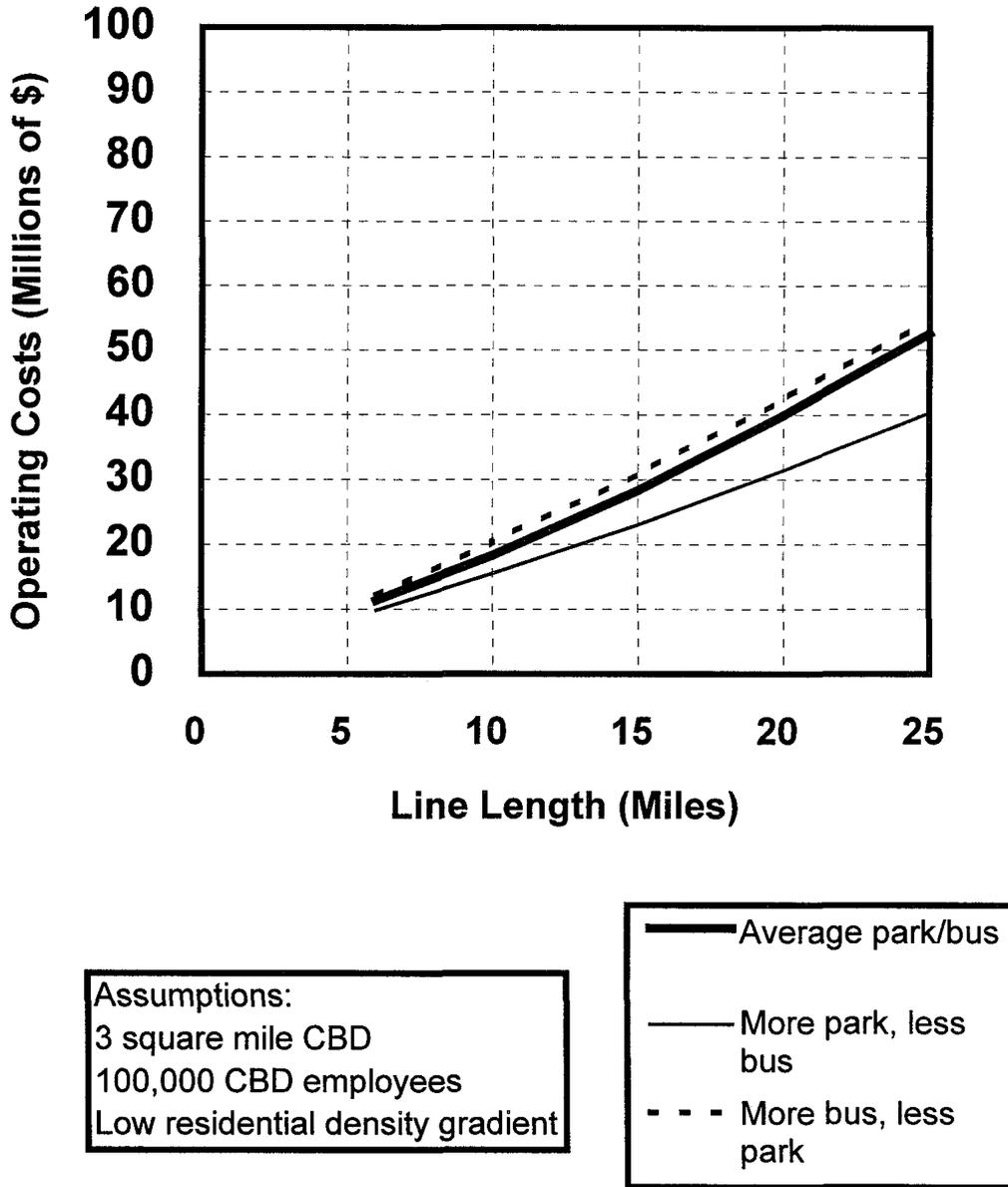
The next series of exhibits displays the annual operating and capital costs for commuter rail. Both sets of curves are shown because operating and capital cost curves for commuter rail, unlike light rail, have different shapes. In the case of commuter rail, the capital costs are more sensitive to line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

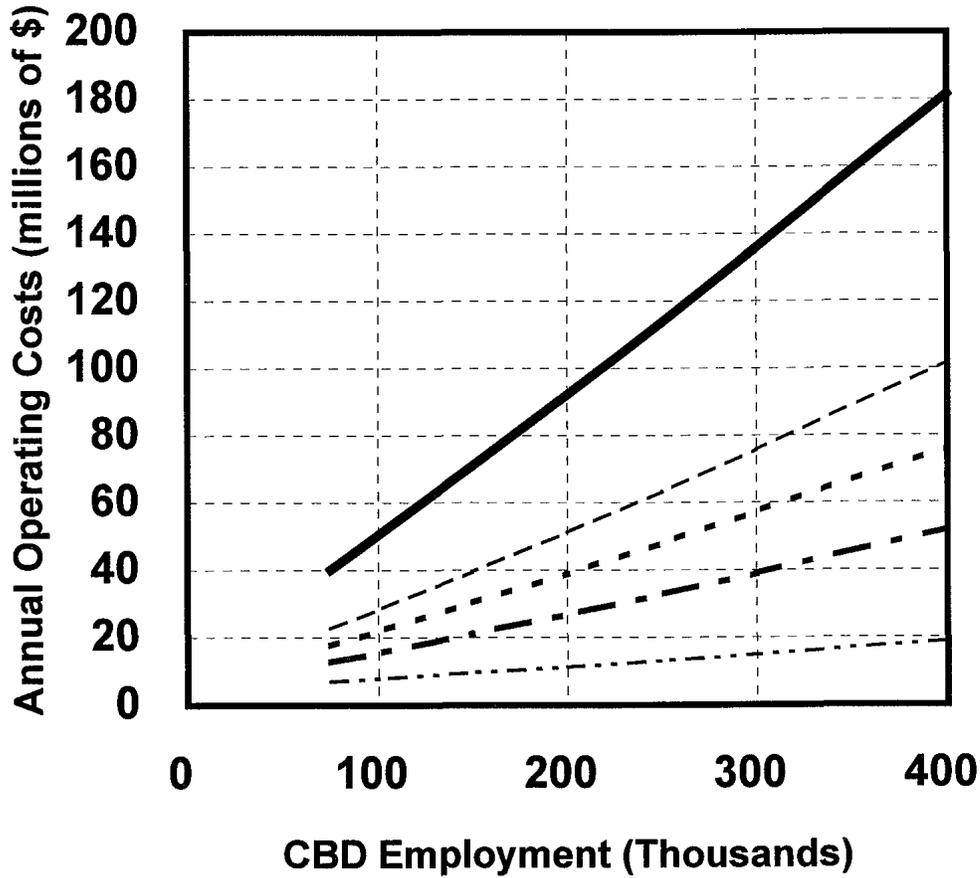
Because the demand curves for varying residential density gradients showed little variation, the cost curves are not shown for these gradients separately. (The reader can refer back to Figure 15 to find the definitions of residential density gradients used for commuter rail corridors.)

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**



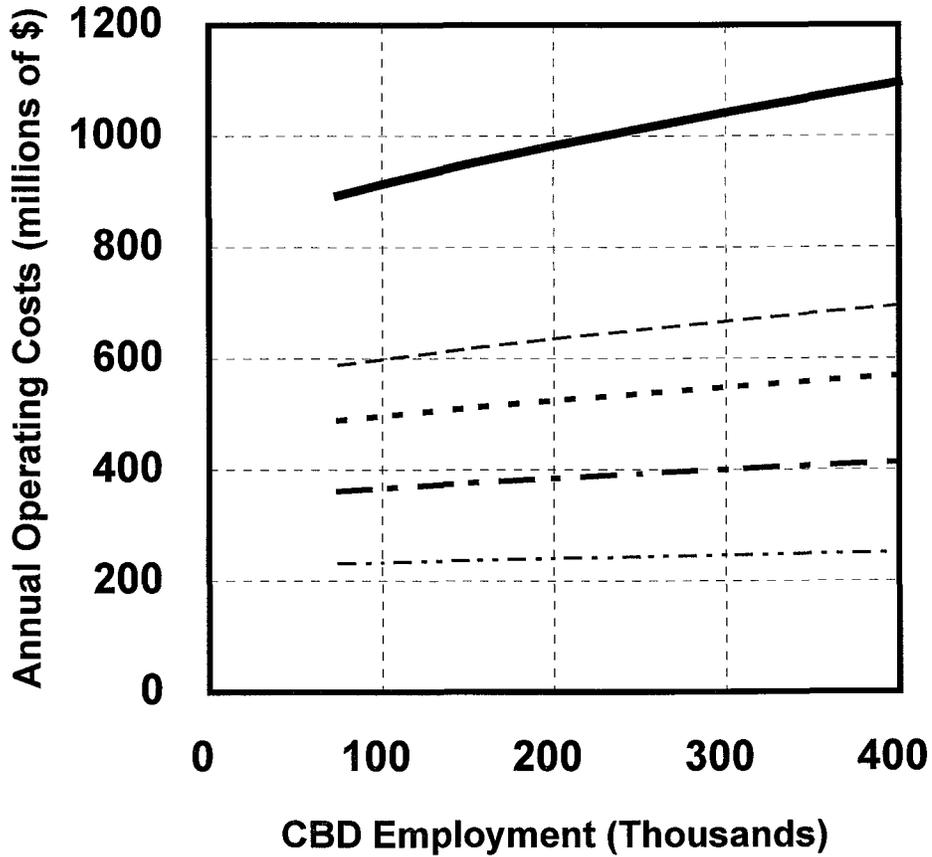
**Figure 32.**  
**Commuter Rail Operating Costs**  
**by CBD Jobs and Line Length**



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

- - - 20-mile line
- - - 30-mile line
- - - 40-mile line
- - - 50-mile line
- 80-mile line

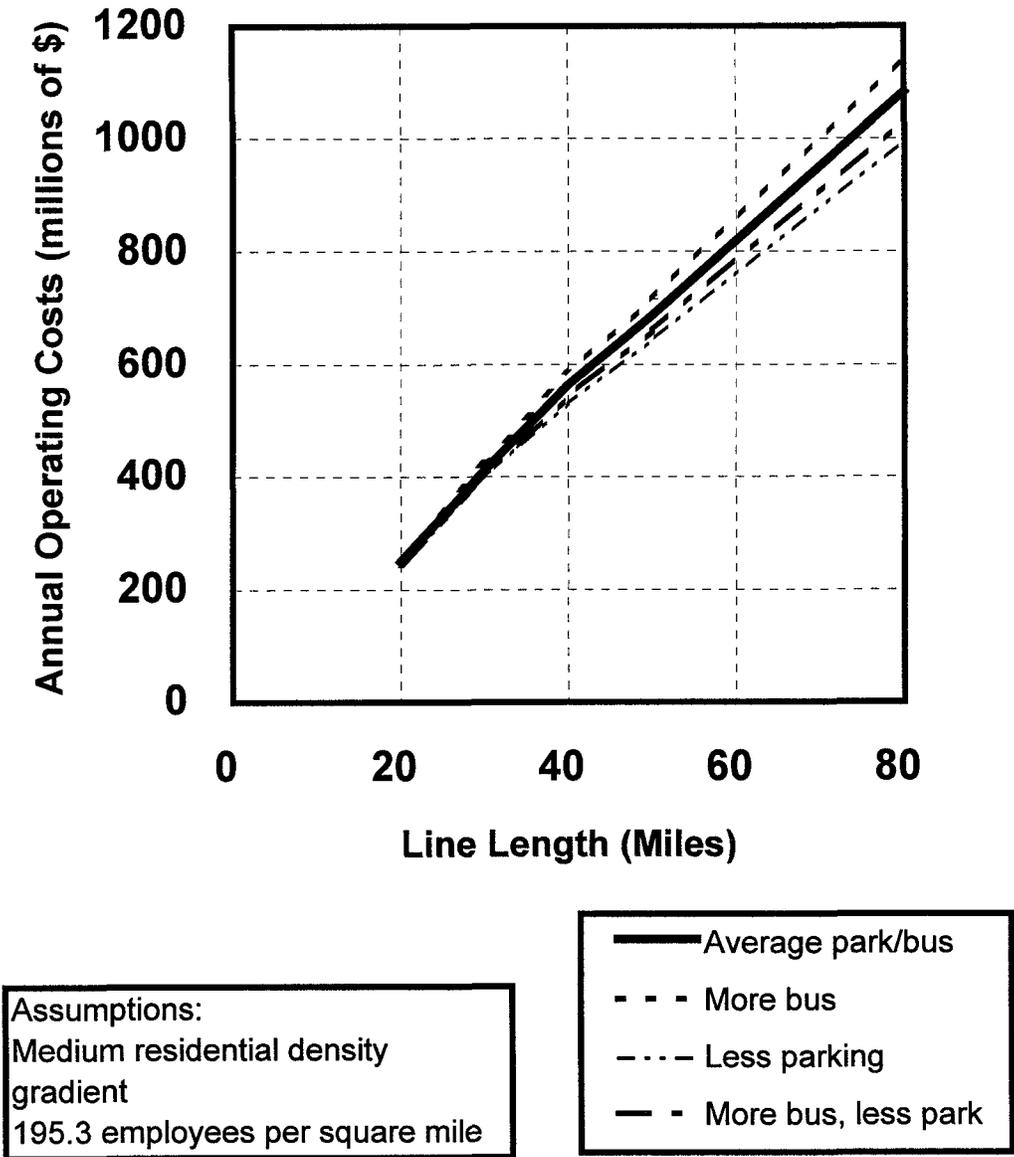
**Figure 33.**  
**Commuter Rail Capital Costs**  
**by CBD Jobs and Line Length**



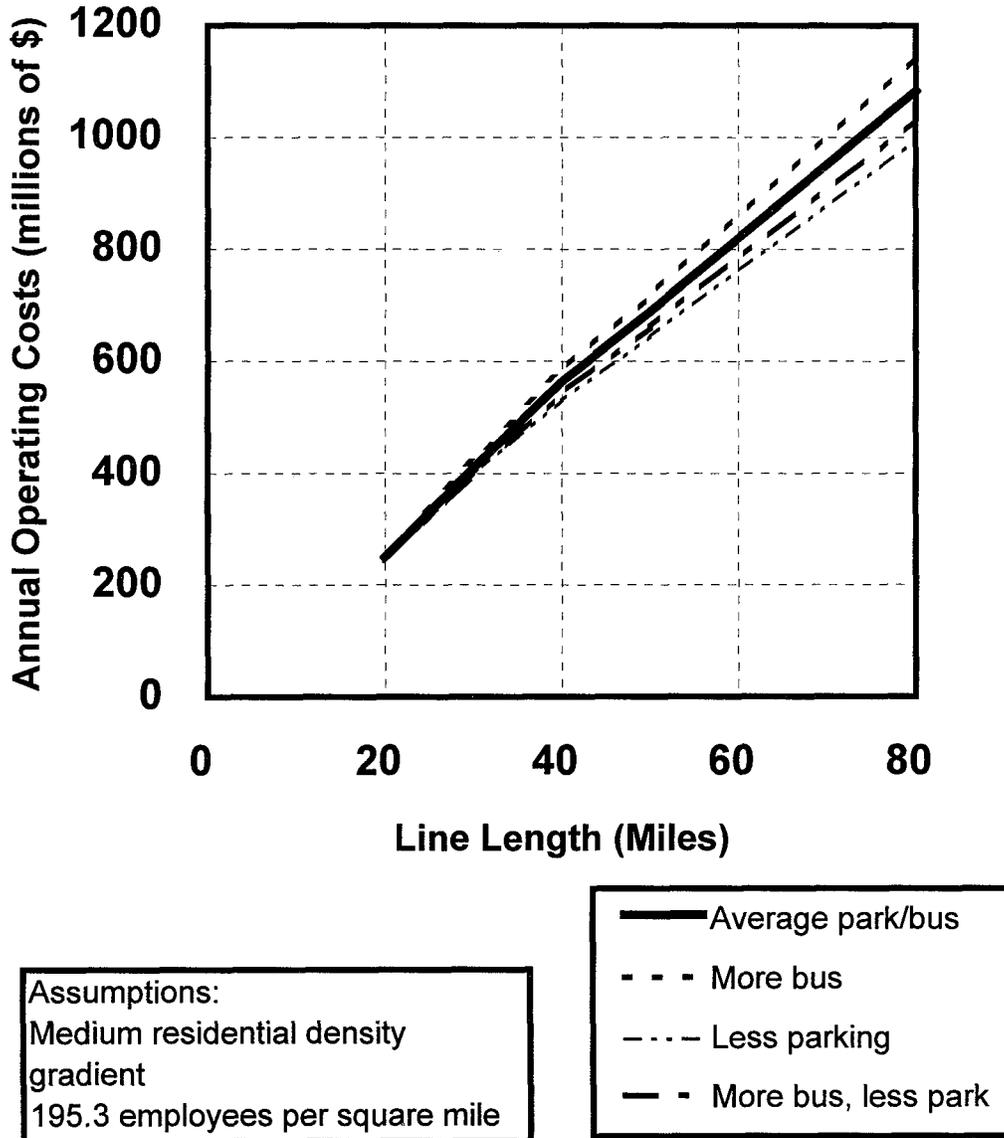
Assumptions:  
 3 square mile CBD  
 High residential density gradient  
 Average parking/bus

- ..... 20-mile line
- . - 30-mile line
- - - 40-mile line
- - - 50-mile line
- 80-mile line

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



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



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 compete 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**

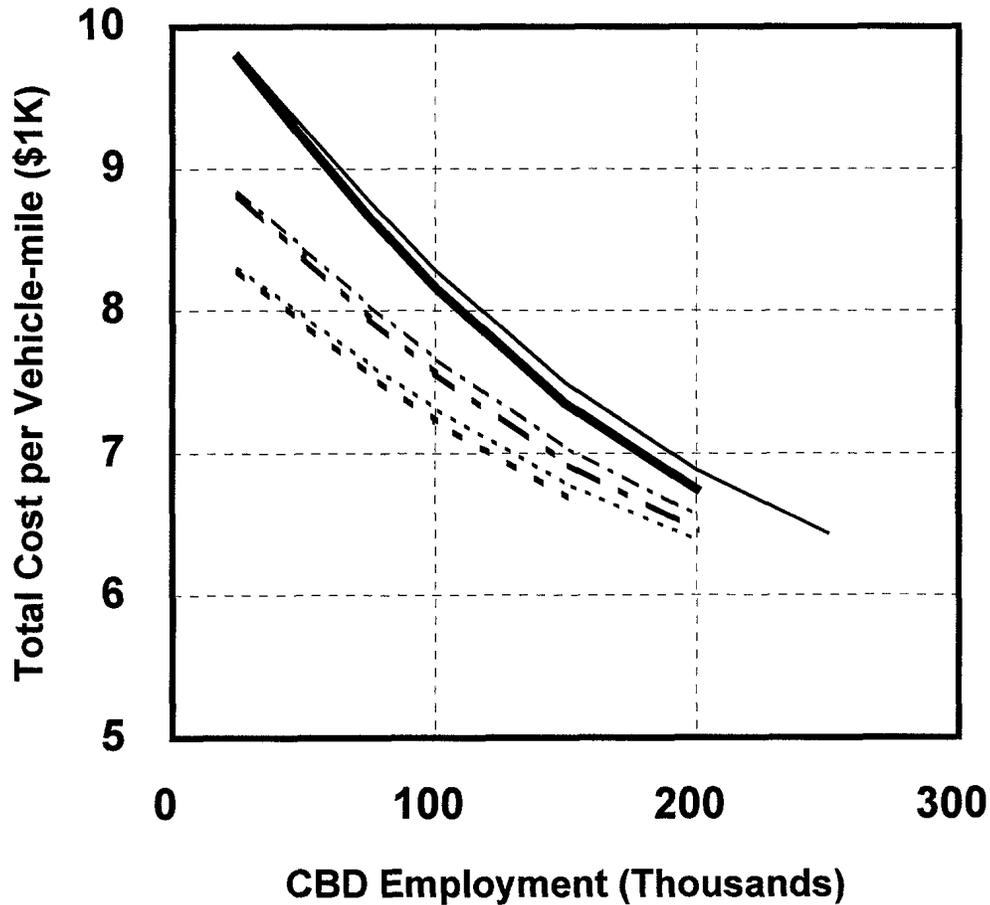
The **total annual cost per vehicle-mile** is plotted against CBD employment and is shown as a family of curves for residential density gradients and employment densities in a series of graphs in Figure 36 through Figure 40. Each exhibit represents a different line length. Each exhibit shows clearly 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)**

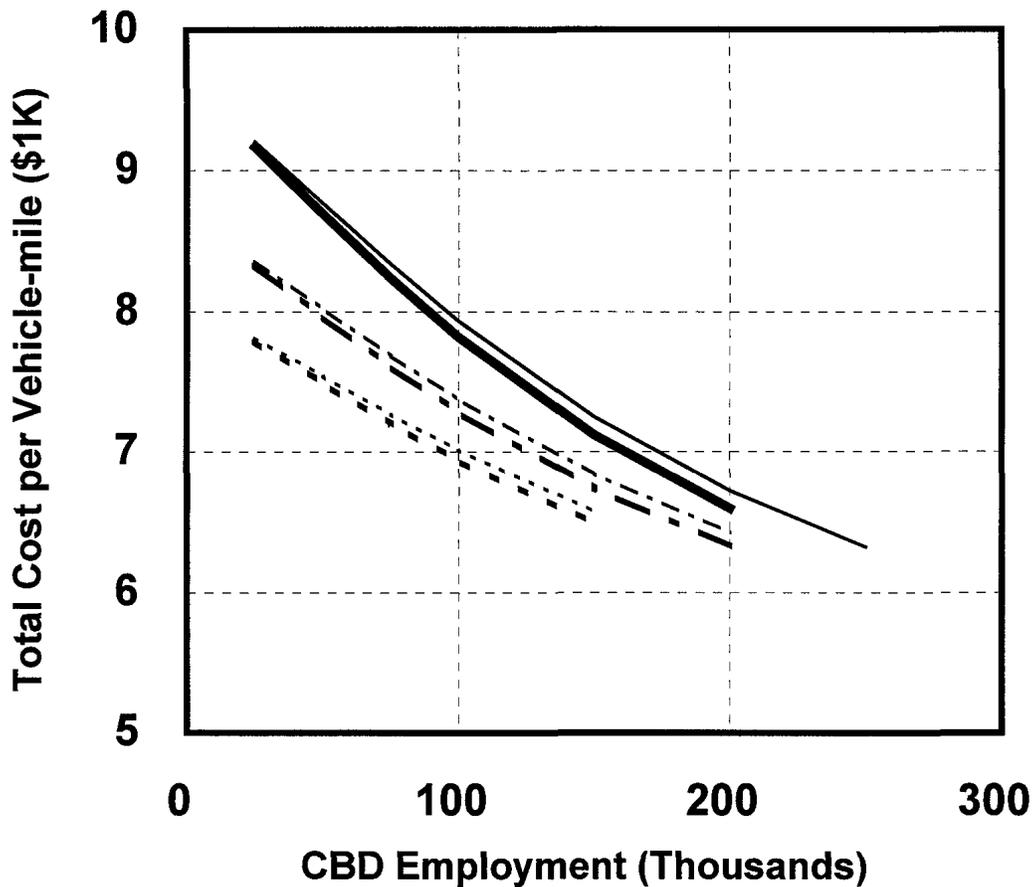


Symbol	Residential Gradient <sup>1</sup>	Employment Density <sup>2</sup>
.....	High	Low
- . - .	High	High
- - - -	Medium	Low
- - - -	Medium	High
————	Low	Low
————	Low	High

<sup>1</sup> Residential density varies with distance from the CBD. Figure 14 illustrates the density gradients.

<sup>2</sup> 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)**

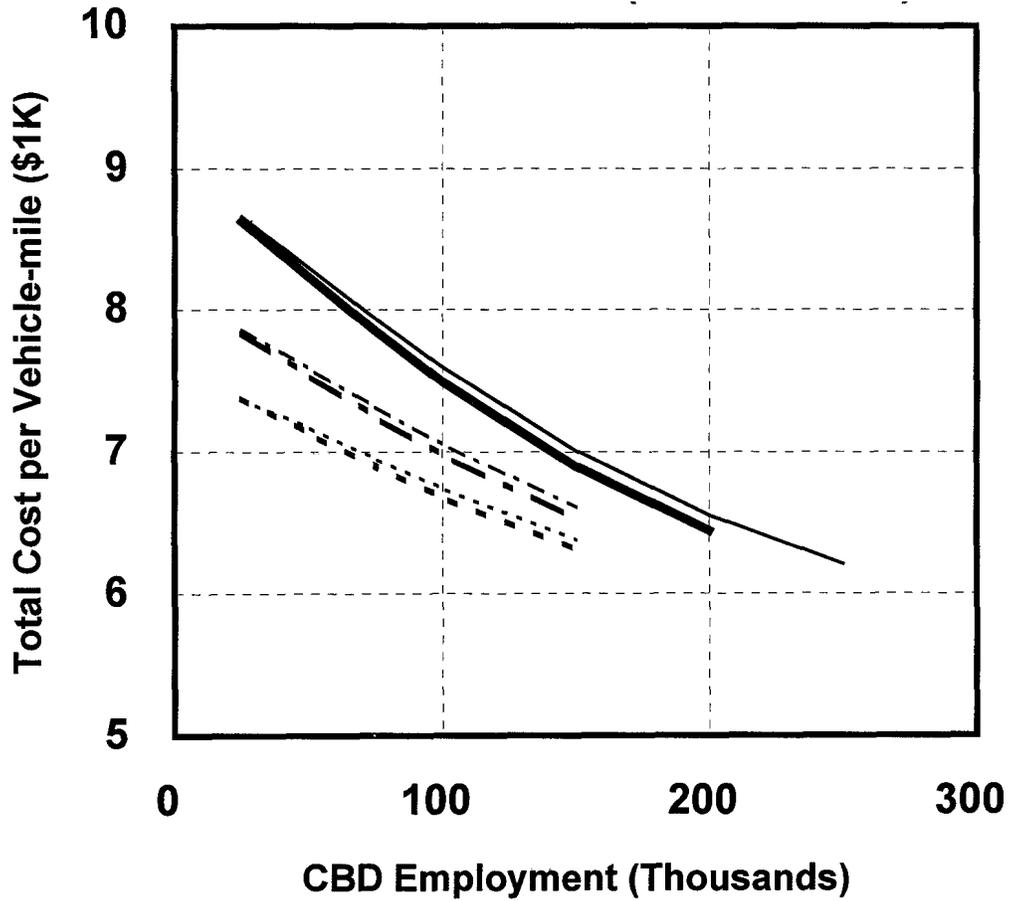


Symbol	Residential Gradient <sup>1</sup>	Employment Density <sup>2</sup>
.....	High	Low
- - -	High	High
- . - .	Medium	Low
- - -	Medium	High
_____	Low	Low
_____	Low	High

<sup>1</sup> Residential density varies with distance from the CBD. Figure 14 illustrates the density gradients.

<sup>2</sup> 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)**

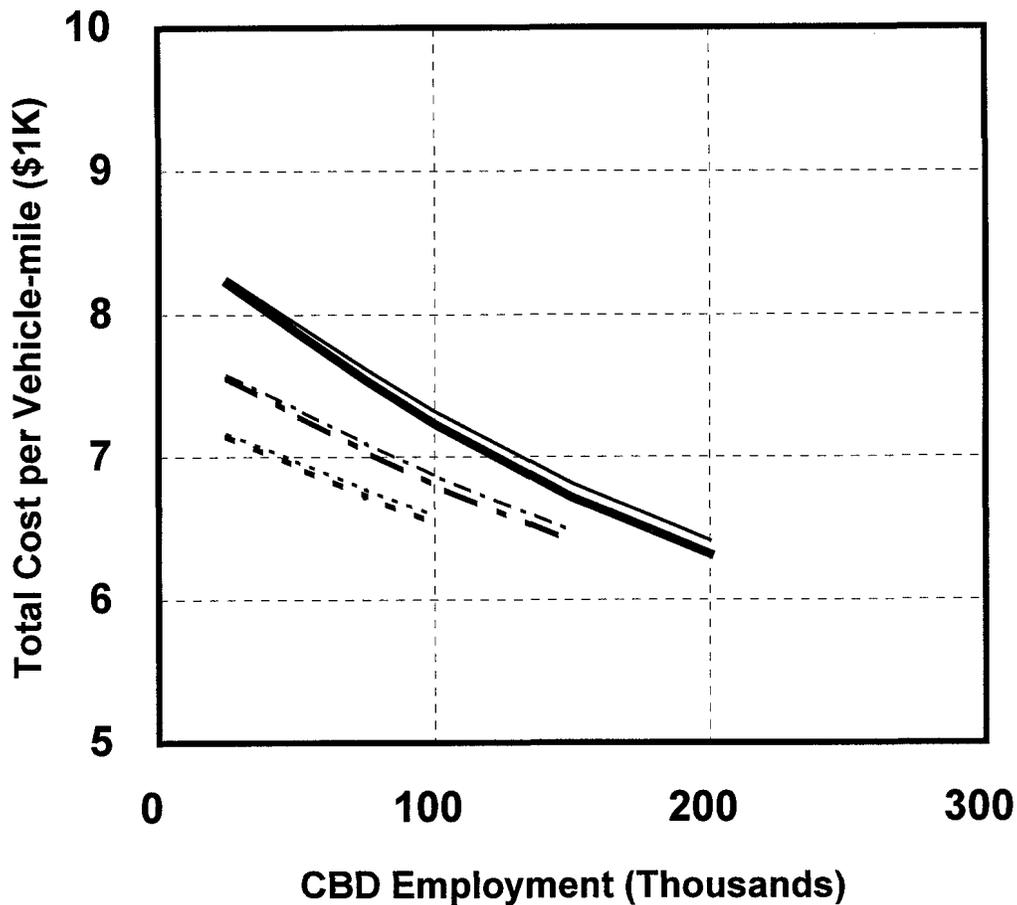


Symbol	Residential Gradient <sup>1</sup>	Employment Density <sup>2</sup>
.....	High	Low
- - -	High	High
- . - .	Medium	Low
- - -	Medium	High
—	Low	Low
—	Low	High

<sup>1</sup> Residential density varies with distance from the CBD. Figure 14 illustrates the density gradients.

<sup>2</sup> 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)**

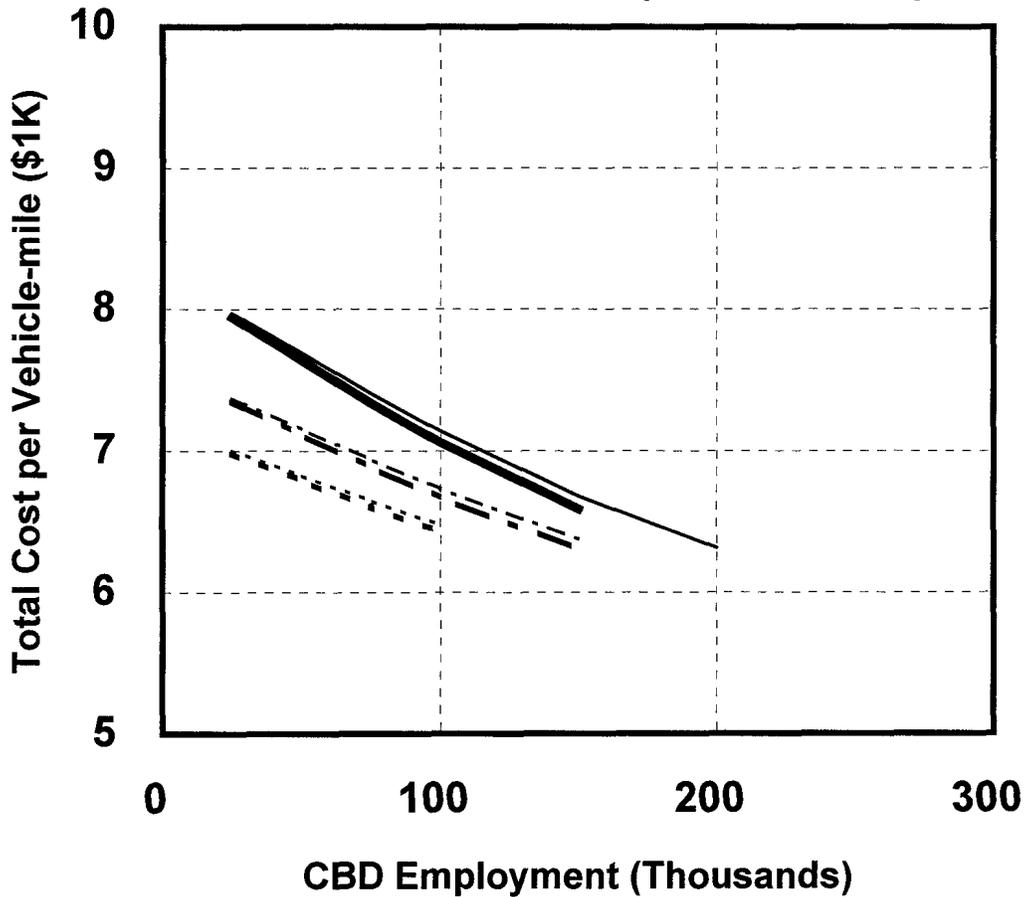


Symbol	Residential Gradient <sup>1</sup>	Employment Density <sup>2</sup>
.....	High	Low
- . - .	High	High
- - - -	Medium	Low
- - - -	Medium	High
————	Low	Low
————	Low	High

<sup>1</sup> Residential density varies with distance from the CBD. Figure 14 illustrates the density gradients.

<sup>2</sup> 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)**

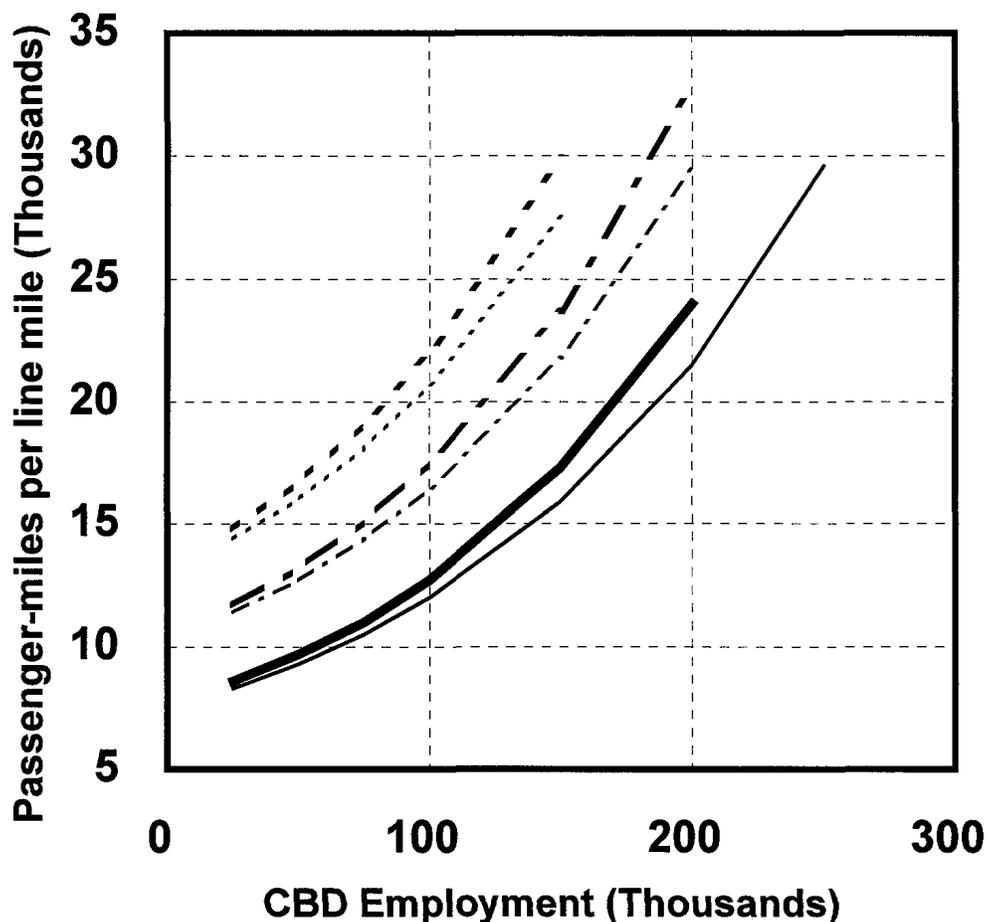


Symbol	Residential Gradient <sup>1</sup>	Employment Density <sup>2</sup>
.....	High	Low
- - -	High	High
- . - .	Medium	Low
- - -	Medium	High
————	Low	Low
————	Low	High

<sup>1</sup> Residential density varies with distance from the CBD. Figure 14 illustrates the density gradients.

<sup>2</sup> 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)**

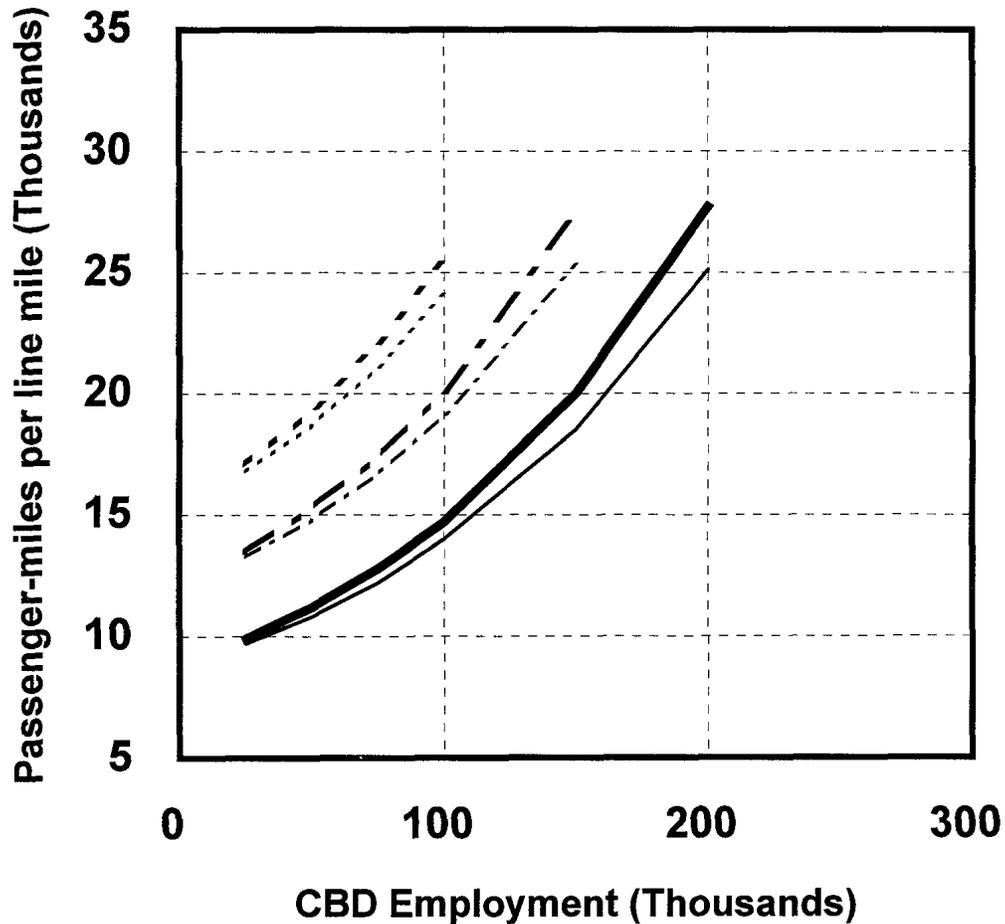


Symbol	Residential Gradient <sup>1</sup>	Employment Density <sup>2</sup>
.....	High	Low
- . - .	High	High
- - - -	Medium	Low
- - - -	Medium	High
————	Low	Low
————	Low	High

<sup>1</sup> Residential density varies with distance from the CBD. Figure 14 illustrates the density gradients.

<sup>2</sup> 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	Residential Gradient <sup>1</sup>	Employment Density <sup>2</sup>
.....	High	Low
- - -	High	High
- . - .	Medium	Low
- - -	Medium	High
— — —	Low	Low
————	Low	High

<sup>1</sup> Residential density varies with distance from the CBD. Figure 14 illustrates the density gradients.

<sup>2</sup> 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**

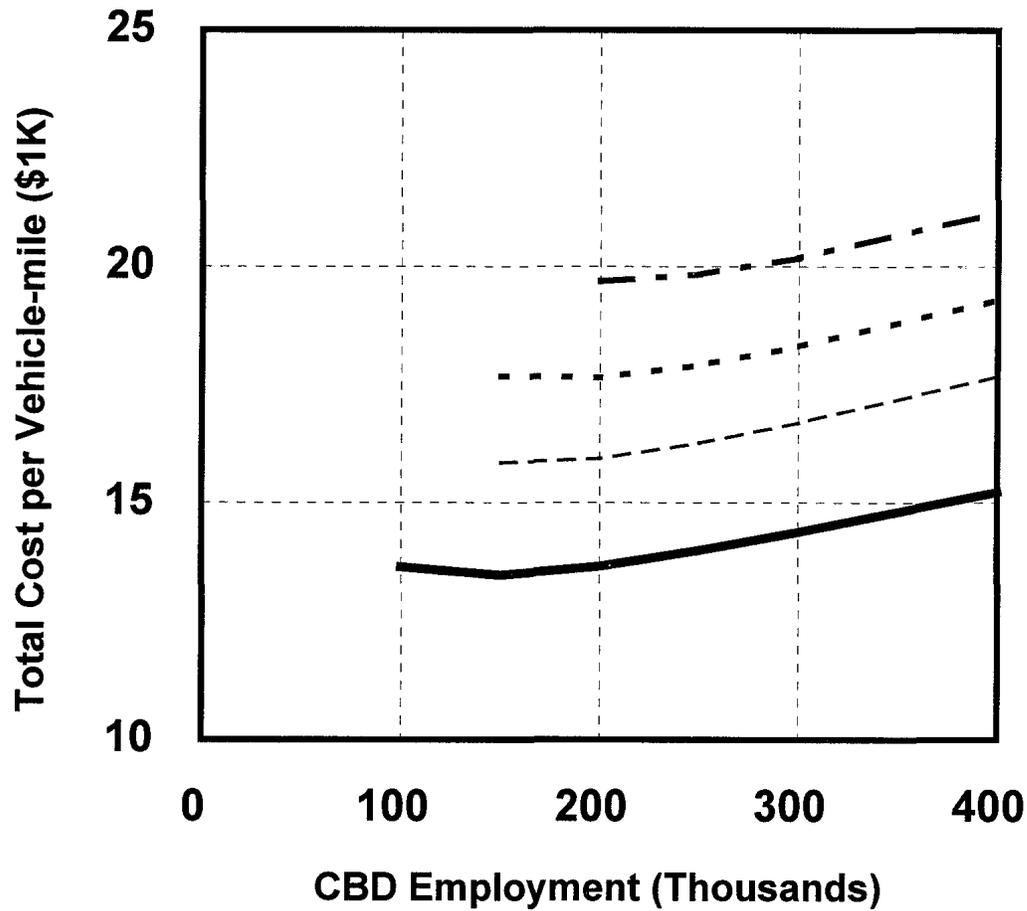
As was done for the hypothetical light rail lines, the total cost per annual vehicle-mile, a measure of cost-efficiency, was calculated. The intent is to show the variation of this important measure as a function of land use characteristics. As will be recalled for commuter rail the residential density 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)**

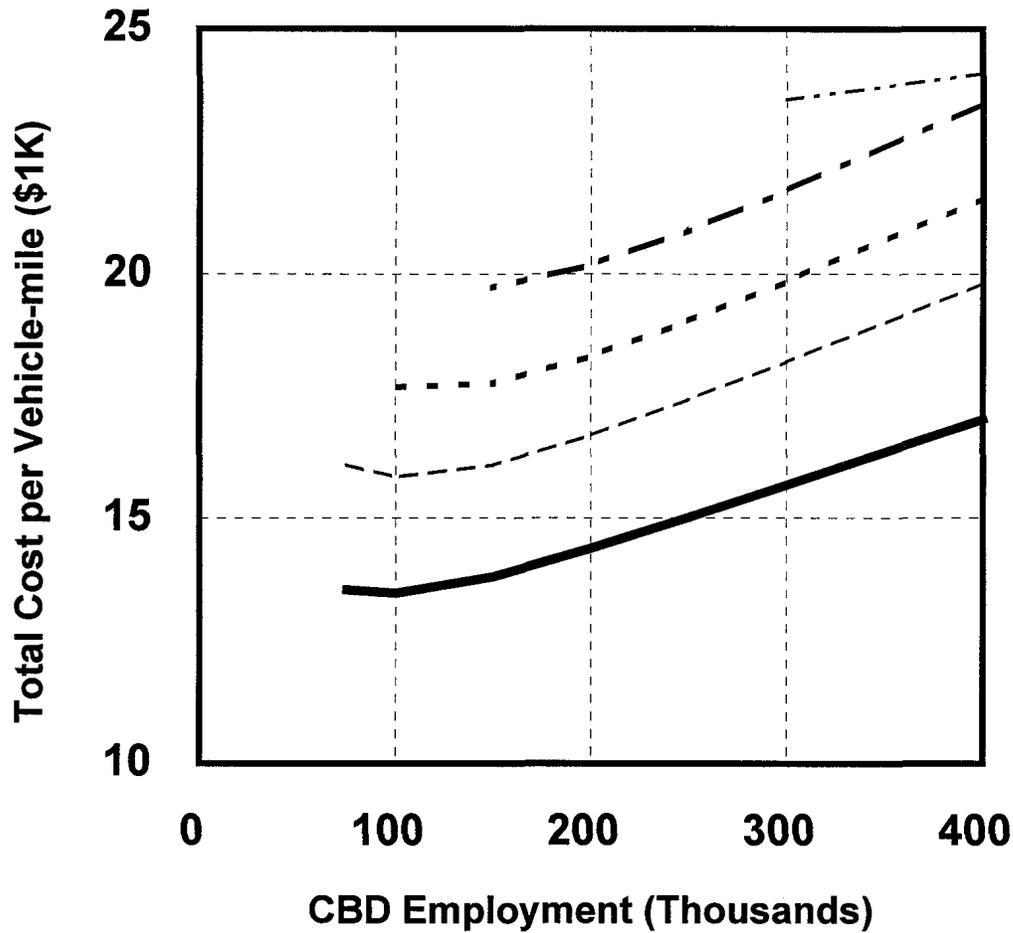


Assumptions:  
 Low density CBD (3 sq. mi.)\*  
 High residential density gradient

— - 30-mile line  
 - . - 40-mile line  
 - - - 50-mile line  
 ——— 80-mile line

\*Note:  
 CBD density varies with CBD  
 employment size.

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

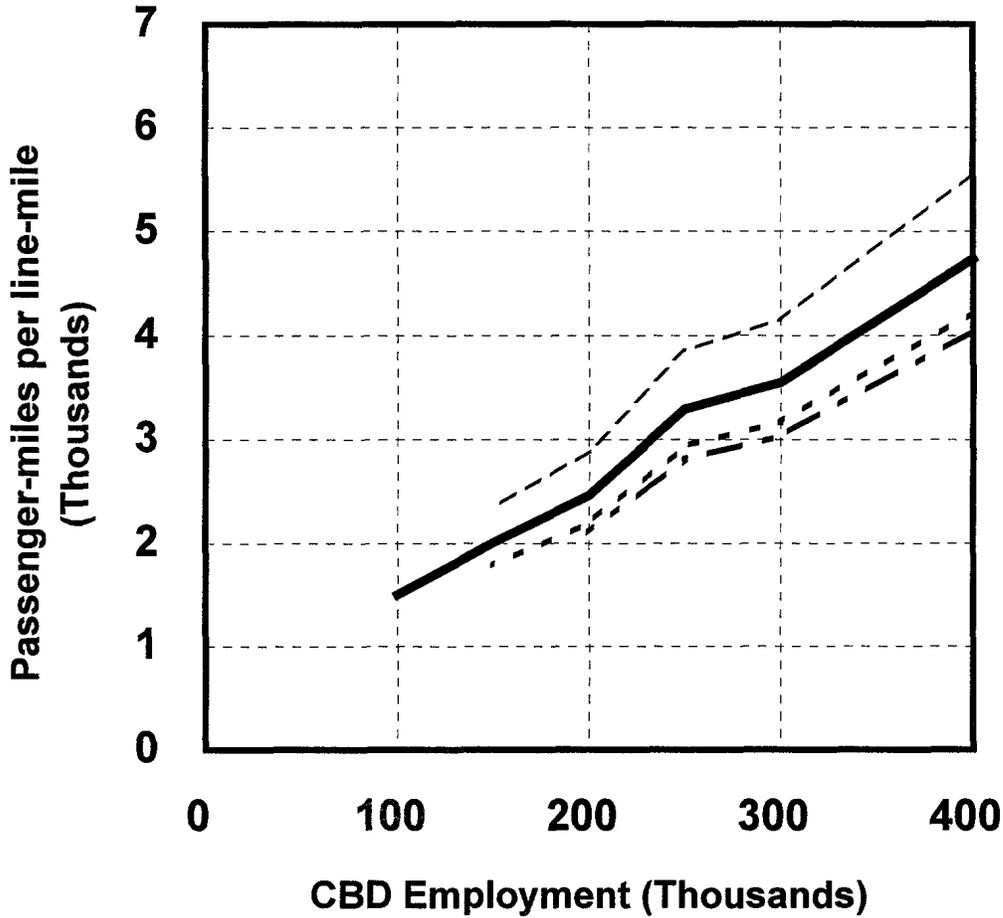


**Assumptions:**  
High density CBD (2 sq. mi.)\*  
High residential density gradient

--- 20-mile line  
- . - 30-mile line  
- - - 40-mile line  
- - - 50-mile line  
— 80-mile line

\*Note:  
CBD density varies with CBD  
employment size.

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

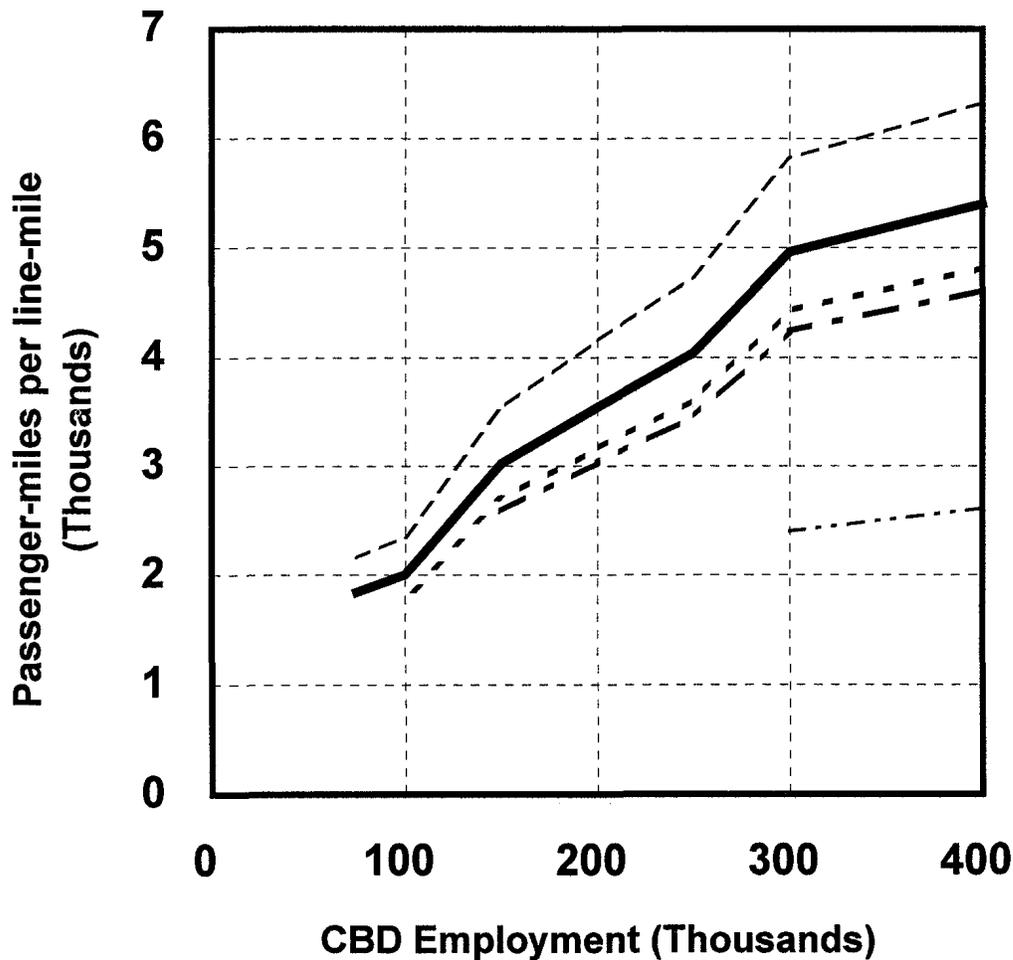


Assumptions:  
Low density CBD (3 sq. mi.)\*  
High residential density gradient

\*Note:  
CBD density varies with CBD  
employment size.

— - 30-mile line  
- - - 40-mile line  
- - - 50-mile line  
— 80-mile line

**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.

--- 20-mile line  
- - - 30-mile line  
- - - 40-mile line  
- - - 50-mile line  
—— 80-mile line

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.