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Introduction

The cost of building rail transit facilities in the United States has skyrocketed in recent decades. Sections of Los Angeles's Red Line subway cost more than $750 million per mile to build and even less pricey light-rail systems can cost more than $200 million per mile. Soaring capital investment costs are today's biggest deterrent, both political and financial, to constructing new transit infrastructure.

It stands to reason that high-cost transit projects need high ridership levels. Without sufficient numbers of riders and the fares they generate, new rail investments will inevitably incur huge deficits. Nor will environmental benefits accrue. Transit only reduces traffic congestion and tailpipe emissions when it draws former motorists – and particularly single-occupant drivers – to trains and buses. A system with few riders and a high price tag is a poor investment compared to a system with many riders and a low price tag.

Through the investigation of more than 50 transit investment projects built in the U.S. since 1970, we find a strong correspondence between costs and ridership. As one would expect, capital costs and ridership are positively correlated. Moreover, both ridership and capital costs typically rise with job and population densities. By clustering trip ends near stops, concentrated development tends to average far more transit trips per square mile than less concentrated development. But density often increases construction costs as well – via increased costs for right-of-way acquisitions and building demolitions, more complicated route alignments, utility relocation expenses, and higher labor costs.

This symbiotic relationship between density and both ridership and costs begs the question: are there densities that offer the most "bang for the buck" in terms of the number of riders for the investment costs? If so, what minimum densities should municipalities zone for around existing or planned stations in different settings or for different types of investments? These are among the most frequently asked questions in the urban planning field today – questions for which there are surprisingly few good answers or widely accepted benchmarks. This paper aims to help fill this knowledge gap.

Policy Context

America has experienced a rail renaissance over the past four decades. More than one thousand miles of light and heavy rail lines – to say nothing of commuter rail – have been built in the U.S. since the 70-mile Bay Area Rapid Transit (BART) heavy-rail system opened in 1973. BART, America's first post-WWII new-generation rail system, came in at $97 million per mile (in 2009 dollars). Three decades later, the extension of BART to the San Francisco International Airport cost more than $180 million per track mile.

The meteoric rise in construction costs for systems like BART has prompted the U.S. Department of Transportation, which historically has picked up 80 to 90 of the bill, to more closely scrutinize proposed projects. This has mainly been in the form of the Federal Transit Administration's New Starts criteria, which rank transit projects based on local financial contribution and project justification, including mobility improvements, environmental benefits, operating efficiencies, cost effectiveness, and transit supportive land use (FTA, 2009). Minimizing capital costs and maximizing ridership are essential to achieving a high rating.

Literature Review

Dense areas both benefit from and support transit. Attempts to quantify the required levels of urban density to support transit have a long history. The most cited study, by Pushkarev and Zupan (1977), looked at eight modes of public transportation: taxicab, dial-a-bus, local bus, express bus, light rail, light guideway transit, rapid transit and commuter rail. To study the characteristics of a city that best explained variations in the cost-effectiveness of these modes, the authors turned to three factors: non-residential CBD floorspace, residential neighborhood densities, and distance to the CBD. Using regression models, these city characteristics were used to estimate travel demand (in terms of one-way trips per square mile) and passenger operating costs, at various service frequencies. Pushkarev and Zupan found that cities with larger CBDs and higher residential densities along linear corridors could support higher levels of transit service.

"Urban Rail in America" (Pushkarev, Zupan, and Cumella 1982) built upon the previous research, focusing on fixed guideway rail investments. At the time, rail transit existed in only six U.S. metropolitan areas. These six areas averaged 20% to 30% fewer auto trips than other large cities and were thus logical candidates to study how city characteristics influenced cost and ridership performance. Under the right circumstances, the authors hypothesized, rail could improve mobility, save energy, and conserve land. The authors argued that the "right circumstances" are dense downtowns with substantial office and commercial floorspace and linear corridors comprised of multi-family housing versus single-family, detached units.

Using data from 24 CBD areas in the New York Tri-State area, Pushkarev et al. (1982) also estimated a demand model that predicted rail trips as a function of non-residential downtown floorspace and population distribution. Non-residential development outside of the CBD were found to significantly influence travel demand: if two similarly sized CBDs have different amounts of suburban office and retail development, the one with the less suburban development will attract more trips to the CBD. Demand for downtown trips was used to determine the level of transit service that a city can support. To justify the cost of a rapid transit investment, the authors set minimum thresholds of about 12 households per net residential acre along a transit corridor and a CBD of at least 50 million square feet of nonresidential development (Table 1). For light rail, minimum density thresholds were lower at 9 households per acre. Based on their estimates, they argued that Los Angeles, Seattle and Honolulu could support heavy rail transit, while Houston, Detroit, Dallas, Baltimore and Miami, were potential candidates for more limited, primarily above-grade investments. They recommended light rail with varying degrees of length and design for Seattle, Detroit, Honolulu, Houston, Dallas, St. Louis, Pittsburgh, and Milwaukee, Minneapolis, Buffalo, San Diego, Indianapolis, Portland, Louisville, Cincinatti and Denver and possibly Columbus, Kansas City and New Orleans. Most of these cities have built some form of LRT in ensuing years. The authors did not evaluate Sacramento or San Jose, and recommended no build in Phoenix -- cities that today operate light-rail services.

Table 1. Transit-supportive density levels adapted from Pushkarev and Zupan (1977)

Mode	Service	Minimum residential units per net acre	Remarks
Local Bus	Minimum (20 bus/day)	4	10 million non-residential CBD s.f.
Local Bus	Intermediate (40/day)	7	
Local Bus	Frequent (120/day)	15	35 million non-residential CBD s.f.
Express Bus (foot)	Five buses in two hour peak period	15 (2 square mile area)	50+ million non-residential CBD s.f.
Express Bus (auto)	5-10 buses in two hour peak period	3 (20 square mile area)	10 to 15 miles from CBD (preferably 20+ million non-residential CBD s.f.)
Light Rail	5 minute peak-hour headways	9 (corridor of 25 to 100 square miles	20 to 50 million non-residential CBD s.f.
Heavy Rail Rapid Transit	5 minute peak-hour headways	12 (corridor of 100 to 50 square miles)	50+ million non-residential CBD s.f.
Commuter Rail	Twenty trains per day	1 to 2	Only to largest downtowns

The Pushkarev et al. results quickly gained notoriety. Pickrell (1985) criticized the study for underestimating the number of trips needed to make transit cost effective. Previous studies had come up with thresholds two to three times higher, as did Pickrell's revised estimates. Pickrell also criticized the Pushkarev et al. work for systematically underestimating the costs of providing transit service. Pushkarev et al. based their estimates on cost data for 20 projects, not including shops, yards, or land acquisition and provided separate estimates for light and heavy rail. Adjusting these costs to 2009 dollars, we find their figures generally consistent with observed costs, although several projects are significantly more expensive. Guideway construction, systems, and soft costs, however, typically accounted for 50% to 70% of total costs in our sample.

As there is no consensus on appropriate cost recovery levels for transit, it is difficult to estimate required ridership levels for given capital or operating costs. As a “merit good” that produces societal benefits (e.g., less traffic congestion, cleaner air), it is generally accepted that transit should not be expected to recover its full costs through the farebox. It is thus hard to pin down a minimum density level needed to generate riders and farebox-income if a targeted cost recovery level is not known. Nevertheless, the fundamental assertion that there are local and corridor-level density thresholds at which transit thrives is still taken as a given.

As more data have become available, analysts have been better able to account for the complexity of factors that impact ridership. In 1996, the Transit and Cooperative Research Program (TCRP) produced a four-part study, “Transit and Urban Form”, that summarized knowledge in the field, reanalyzed and updated Pushkarev and Zupan's work on fixed-guideway-transit-supportive land use, and provided a guidebook for practitioners to plan around transit. Part II of the study modeled ridership for 261 light rail stations from eleven metropolitan areas and 550 commuter rail stations from six areas using multivariate ordinary least squares (OLS) regression (Parsons, Brinckerhoff, Quade & Douglas, Inc. *et al.* 1996). Explanatory variables included miles and minutes that a station lies from the CBD, miles to nearest station, a terminal station dummy variable, and number of parking spaces and population density within a half-mile ring of station platforms. Findings confirmed a strong relationship between the explanatory variables, residential density and CBD size, and the dependent variable, number of boardings at light-rail stations. Population density had less influence on commuter rail ridership. More important were parking supply and CBD size. A doubling of residential density correlated to a 59% and 25% increase in ridership respectively.

Cervero (2006) reran the TCRP model for light rail but included a dummy variable for whether a station was in the CDB and a measure of service intensity, which tends to be higher in denser areas. This model produced a much lower elasticity, with a doubling of density correlating to a 19% increase in ridership.

Recent studies have also focused on the relationship between urban densities and ridership at what many consider to be the correct “ecological unit” -- the individual rider. Cervero (2007) examined the housing location and mode choice decisions of more than 11,000 individuals from the 2000 Bay Area Travel Survey, using binomial logit analysis to model how proximity to transit affects an individual’s decision to commute by transit. These mode choice decisions were nested within the decision whether to live within a half mile of transit to correct for residential self-selection bias, the phenomenon whereby researchers may over-predict the effects of the built environment on travel since households that locate near transit are the households often most likely to take transit in the first place. He found that out-of-neighborhood network characteristics, like accessibility to jobs, increased the probability that someone living near transit will take transit far more than the neighborhood characteristics around the origin station. After all, someone living next to transit station cares a lot more about where that transit system goes than whether it is surrounded by other houses or jobs when deciding whether to take the train. The more people there are living around a station, however, the more people there are to take the trains. An area of 10,000 commuters with an average 30% probability of taking the train will generate twice as many riders as an area of 3,000 with a 50% probability.

Ideally, researchers would model national transit ridership by estimating all households’ probability of taking transit at specific stations and apply a weighted average to total number of motorized trips being made. This approach is currently only feasible in those metropolitan areas that have conducted their own surveys or paid to supplement the National Household Transportation Survey. Data limitations generally preclude the ability to derive national ridership estimates from highly disaggregate data and choice models.

Built Environments and Transit Travel

Studies on density and transit ridership are part of a rapidly expanding literature on how built environments influence travel behavior. Many empirical studies have adopted the 3-D (density, diversity, design) framework introduced by Cervero and Kockelman (1997), which in recent years have been expanded to five (adding destinations and distance-to-transit) or more dimensions (Ewing and Cervero, 2001; Ewing and Cervero, 2010). Density and urban design tend to exhibit what Cervero and Kockleman (1997) term as “extreme multicollinearity”. “[H]igh density neighborhoods tend to have local shopping, good public transit, sidewalks, slow vehicle speeds, and to be located near job centers (Holtzclaw et al. 2002).” Attempting to disentangle the variety of effects yield differing and sometimes conflicting results, depending on what variables are included and what statistical models are employed. Many measures of micro-level built form correlate strongly with metropolitan attributes. For example, the densest residential neighborhoods are, by and large, in the biggest metropolitan areas.

To date, over two hundred empirical studies have investigated the link between the built environment and travel (Ewing and Cervero 2010). Density is defined, among other ways, as population, households, population and jobs, lane miles, transit seat miles per day, or number of retail shops over some defined space, which may or may not net out open space, bodies of water or empty parcels. Density also varies within metropolitan areas. This variation may have significant travel implications. Manville and Shoup (2005) argued that while having a high metropolitan density, excessive parking requirements in Los Angeles have prevented the emergence of a dense downtown core that would support transit and non-motorized transport (NMT). Another caveat is that the denominator of density measures is often treated inconsistently. Residential densities can vary a lot depending on whether number of housing units are indexed to total land area (e.g., gross densities), residentially zoned and used land area (e.g. residential densities), or residential areas excluding schools, roads, water bodies, steep slopes, etc. (e.g., net residential densities). If 100 dwelling units lie within 10 acres, half of this area is for residential uses, and half of the residential area goes for roads, public spaces, and the like, the results densities are 10 units per gross acre, 20 units per residential acre, and 40 units per net residential acre.

One way to cope with the high multicollinearity of “D” variables is multivariate factor analysis. Cervero and Kockleman (1997) used factor analysis to combine dozens of variables into three overarching factor categories, the so-called 3Ds: density, diversity and design. These factors were then used to explain variation in vehicle trip rates and mode choice for residents of the San Francisco Bay Area residents, using household level socioeconomic and travel data from the 1990-1991 Bay Area Travel Survey. With elasticities ranging from .06 to .18, the 3Ds were found to exert statistically significant but marginal impacts, with density factors having the largest effects. Micro design elements, although carefully collected, had no discernible effect on travel. When household socioeconomic data, such as household size, income and number of cars, were added to the analysis, design and density factors lost much of their predictive power, although they remained statistically significant. The authors argued that a synergistic combination of built environment characteristics is necessary to impact travel decisions.

The Cervero and Kockleman study has been followed by hundreds of empirical investigations that have further probed influences of built environments on travel, many which have taken advantage of advances in GIS data files (Boarnet and Crane, 2001; Ewing and Cervero, 2010). An example is the work of Chatman (2008), who used computer-assisted household surveys in California to study the impacts of the built environment and socioeconomic factors on households' non-work travel. In another paper using the same data, Chatman (2009) explicitly accounted for residential self-selection, finding that it had smaller impacts than socioeconomic or built environment factors on travel. To separate and control for factors influencing travel, he expressed built environments in terms of: (1) measures of activity density – the number of non-work destinations in an area; (2) built environment density – measures of net density of jobs and residents; and (3) network load density – the number of residents and jobs per lane mile. Network load density was found to have the greatest impact, with an increase of 1000 residents per road mile correlating to a 63% reduction in non-work trips by automobile and a 51% increase in non-work NMT. Activity and built environment measures exerted much weaker influences. This implies that an increase in density, with a corresponding increase in road capacity, will have little impact on VMT (vehicle miles traveled), and thus presumably on transit ridership as well. In combination, high activity densities and low network load densities result in more non-work auto trips. A recent structural-equation analysis of 370 U.S. metropolitan areas corroborated the findings of Chatman, showing that high road densities tended to offset the VMT-reducing impacts of high population densities (Cervero and Murakami, 2010).

Perhaps the broadest glimpse into the influences of built environments on travel comes from the recent meta-analysis by Ewing and Cervero (2010). Based on the several hundred studies reviewed, the authors found that measures of destination accessibility and street network design most strongly influence VMT. When controlling for the other factors, population and jobs density appear to exert a weak influence on individual transit use, with average elasticities of 0.07 and 0.01 respectively. Proximity to transit and design more strongly influenced transit ridership. Holding all else constant, doubling the distance to the nearest transit stop corresponds with 29% fewer transit trips. This gives credence to a basic tenet of TOD (transit oriented development): the more people living near transit, the more who will ride it.

Capital Costs and Ridership

A flurry of studies in the 1990s equated urban rail investments in America to pork-barrel politics. Perhaps most notable was the work of Pickrell (1990; 1992). Looking at ten transit investments from the 1980s, Pickrell found that projections systematically overestimated ridership – nine out of the ten did not achieve 50% of projected ridership – while systematically underestimating capital costs – only 2 projects cost within 20% of forecasts. Widely cited, the Pickrell report came to symbolize the exaggerated benefits and understated costs of rail transit projects.

An FTA study on the capital costs of Heavy Rail and rapid bus (Amodei & Schneck, 1994) explicitly stated that it was not a follow-up to the Pickrell report, but an attempt to help policy makers understand and better forecast capital costs. The study presented capital cost data but did not analyze them or make any specific recommendations. Kain (1999) used Pickrell's cost and ridership data to conclude that bus is almost always a more cost-effective option than rail and suggested that light rail projects in a number of U.S. cities were moving forward based on cooked-up ridership numbers and deceitful cost estimates. A study of the General Accounting Office (2001) pitted bus rapid transit (BRT) against LRT investments. The GAO study found that cost per linear mile of BRT was lower than that of light rail, but did not consider ridership levels or important investment attributes such as the percent of the alignment below grade or whether was in an urban area or along a suburban highway. The GAO study also found that many transit officials believe that LRT investments confer significant economic development benefits, and that these alone often justified capital expenditures.

Over the last decade, the FTA sponsored two additional studies on the predicted and actual ridership and capital costs of fixed guideway transit projects. Projections have improved markedly since the initial Pickrell report. Examining 19 projects between 1990 and 2002, Lewis-Workman et al. (2008) found that capital costs exceeded estimates by an average 21% during alternatives analysis and 7% during the Full Funding Grant Agreement. More than half of the projects achieved ridership levels below projections, 32% were within 20% of projections, and 11% exceeded them. The projects completed between 2001 and 2007 – 12 light rail, 4 heavy rail, 4 commuter rail and one bus rapid transit – exceeded capital cost estimates by 40% during alternative analysis and 6% during the Full Funding Grant Agreement. One particular project, the Tren Urbano in San Juan, far exceeded cost projections and drove up the average. Today, FTA expects average ridership for all projects to attain 75% of the levels projected during the alternatives analysis. Cost and ridership projections have gotten more accurate but still tend to exaggerate ridership benefits and underestimate costs. This overestimation is by no means unique to the transit sector, but rather seems endemic to most large-scale infrastructure projects (Altshuler & Luberoff, 2003; Flyvbjerg, Holm, & Buhl, 2002; Siemiatycki, 2009).

The second update of the Pickrell study, by Booz Allen Hamilton (2003), analyzed the capital cost elements of 24 light rail investments. The researchers found: (1) smaller LRT projects are more expensive on a cost per unit basis, (2) projects with more variation, particularly in alignment mix, are more expensive, and (3) general differences in project attributes, such as the percent below grade, utility relocation, and right-of-way acquisitions, are strong cost determinants. A follow-up study (Booz Allen Hamilton, Inc., 2005) looked at factors contributing to cost overruns for light rail projects with an eye toward containing costs. After sharp growth in costs in the early 1990s, the study team found no significant cost increases over the preceding decade. They did, however, identify the construction of light rail systems with heavy catenaries as a major factor that drove up capital costs. They also found that right-of-way acquisition increased at twice the rate of other costs between 1985 and 1994 and that standardized light rail designs were generally less expensive than custom ones.

The past several decades of cost assessments has prompted the FTA to apply a litmus test to new fixed-guideway proposals. When assessing the cost-effectiveness of New Starts and Small Starts applications, the FTA evaluates the hourly in- and out-of-vehicle time-savings to regional travelers divided by the annualized capital and operational costs of the new transit project. Projects with an hour savings for \$11.99 (in 2009 dollars) and under receive a high rating, while those with \$30 and over receive a low rating. In fiscal year 2010, the FTA recommended 40 preliminary-to-final-design project applications for funding. No New Starts and 2 Small Starts applications, achieved a high cost-effectiveness rating (FTA, 2009).

Research Approach and Dataset

This study extends the work of Pushkarev, Zupan, and others by modeling the relationship between investment costs and urban densities for recent fixed-guideway transit investments, controlling for other factors that influence costs. As noted, our aim is to help with the setting of minimum thresholds for population and employment densities as part of the planning and investment in fixed-guideway transit systems.

We estimate the total capital cost, average weekday ridership, and cost per rider of fixed-guideway transit investments as a function of population and employment densities and other control variables. Included here were size, length, type, and design characteristics of projects, average densities surrounding a project’s stations, and fixed-effect dummies that capture some of the unique and possible idiosyncratic characteristics of projects or cities. Densities were estimated for one-half mile rings of stations and then combined to yield a blended average density for an entire project corridor. Dummy variables for projects before 1990, as well as the number of years since the project opened, were included in the models but dropped, contrary to our expectations, due to statistical insignificance.

We were also somewhat surprised not to find a statistically significant relationship between ridership and the number of jobs in the CBD, distance to downtown, or the number of bus transfers along the corridor, since all three of these variables have previously been found to have significant effects. We believe that these variables do, in fact, influence ridership but that with only 59 cases in 22 cities, the resolution of the analysis was too low to capture them. Furthermore, many of the corridors contain large portions of the CBD jobs, creating some multicollinearity issues with job density. We believe, and indeed have found, that these variables have statistically significant effects when using the transit station, rather than the corridor, as the unit of analysis. We also tested median incomes, racial characteristics, percent homeowner, average rents and other socio-economic neighborhood characteristics that theory indicates may influence travel or capital costs.

Table 2 provides background and descriptive data for the dependent and predictor variables used in the analysis. We note that one shortcoming of the database is that the years for variables used in the analysis do not match. Density data, for example, come from the 2000 census whereas capital cost data were taken over many years during which projects were built (adjusted to 2009 dollars). Data limitations make such inconsistencies unavoidable but need to be weighed nonetheless when interpreting results.

Table 2. Descriptive Summary of Variables

Name	Description	Mean	Std. Dev.	Min	Max	Source
Stations	Number of Stations in Alignment	13	10	2	59	Various*
Route Miles	Route Miles of Track by Mode	13	11	1	72	Various*
Percent Subway	Percent of Alignment below Grad	22%	32%	0%	100%	Various*
Parking	Average Parking per Station	375	525	0	2811	Various*
Train Frequency	Average Number of Weekday Incoming and Outgoing Trains from 7:30am to 8:30am	17	8	6	43	Various*
Jobs per acre	Average Jobs per Acre within a Half Mile of Alignment Stations	23.3	22.0	1.1	104.3	2000 Census Transportation Planning Package and CTOD**
Population per Acre	Average Population per Acre within a Half Mile of Alignment Stations	10.6	8.7	1.4	53.0	2000 Census and CTOD**
Regional Population	Population in Metropolitan Area***	4,660,000	4,320,000	100,000	15,320,000	2000 Census and CTOD**

* Transit agencies, Booz Allen Hamilton, Inc and Amodei (1994), GAO (2001), Booz Allen Hamilton, Inc. (2003), and Lewis-Workman et al. (2008)

** Center for Transit Oriented Development (2006)

*** Cities, not in the central metropolitan city (San Jose, Trenton, Newark) use city population.

The analysis was carried out using data on 59 capital transit investment projects in 19 metropolitan areas in the United States. The 59 projects ranged between 2 to over 30 stations per project. Thirty-three of the projects are light rail (LRT) investments; twenty-three, heavy rail (HR); and four, bus rapid transit (BRT). Collectively, these 59 projects had 768 transit stations and 740 bidirectional route miles of fixed-guideway service (i.e. half the number of track miles, given consistent double tracking), and were built at a total 2009-adjusted cost of $68 billion.[1] Capital cost figures and alignments came from of the studies previously cited: the General Accounting Office report (2001) as well as four cost-performance reports prepared for FTA between 1994 and 2007 (Amodei & Schneck, 1994; Booz Allen Hamilton, Inc., 2003; Lewis-Workman, White, McVey, & Spielberg, 2008).[2]

Average weekday ridership and station parking counts were compiled from the online documents, websites, and unpublished records for the 22 different transit agencies included in the study. Ridership at a station was considered to be the average of weekday alightings and boardings, or one or the other, when both counts were not available. Although the majority of counts came from September 2009, several agencies were unable to provide counts for this month, thus we instead relied on the most recent non-summer figures or average annual weekday ridership. Data on parking include counts of spaces at public park-and-ride facilities, but not off-street parking spots. Ridership figures were summed across stations within the corridors that made up this study's 59 projects. Although corridor extensions may encourage existing transit riders to switch from existing stations to new ones, we were unable to exclude these riders from our counts of average daily ridership. However, the countervailing effects of increased ridership at central stations due to system expansion were also not included. The study did not consider whether riders were drawn from rapid transit, buses, cars or other modes.

Table 3. Fixed Guideway Corridor Projects by Mode

		Capital Costs		Average Weekday Ridership		Cost per Rider		Cost per Mile		
Mode	**N**	**Average**	**Stand Dev.**	**Average**	**Stand Dev.**	**Average**	**Stand Dev.**	**Average**	**Stand Dev.**	**Cities Included**
Heavy Rail	23	$2,106	$1,729	65,561	66,528	$126	$72	$231	$162	Atlanta, Baltimore, Boston, Los Angeles, Miami, San Francisco, Washington DC
Light Rail	33	$624	$462	21,466	19,014	$156	$154	$54	$40	Baltimore, Buffalo, Dallas Denver, Jersey City, Los Angeles, Minneapolis, Newark, Phoenix, Portland, Sacramento, San Diego, San Jose, St. Louis
Bus Rapid Transit	4	$303	$253	13,347	6,362	$67	$63	$50	$59	Boston, Cleveland, Eugene, Los Angeles

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[1] Capital costs are inflated using the Bureau of Labor Statistics' Consumer Price Inflation (CPI) calculator. CPI was used instead of Producer Price Inflation in order to avoid favoring projects built in more recent years.

[2] Cost figures included right-of-way acquisition, construction, soft costs, initial rolling stock, required service station upgrades or construction, and infrastructure relocation and other unique costs. Previous Booz Allen Hamilton studies adjusted capital costs using separate inflation adjusters for different types of capital costs, but detailed cost breakdowns were not available for all 59 projects.

The average cost per mile was estimated by taking the total capital investment cost and dividing it by the bidirectional linear miles of rail or busway. Estimating cost per rider posed more difficulties since ridership counts vary by length of time (i.e., annually, monthly, average daily). We opted to index costs to annual ridership. We took the 2009-adjusted capital cost figure of each project and divided this by the average weekday ridership figure multiplied by 325 (yielding an estimated total annual ridership). Dividing capital cost per annual rider by the expected lifetime of a project gives a rough approximation of the capital cost per transit ride over a project's service life. The average heavy rail project for example was $4.80 to $2.40 per ride, assuming a lifespan of 25 to 50 years. Table 3 provides summary statistics by mode on project costs, ridership, and costs per mile and per average annual rider.

Capital rail projects are often normalized and compared on a cost per mile basis (Booz Allen Hamilton, Inc., 2003; GAO, 2001; Pickrell, 1992; Pushkarev, Zupan, & Cumella, 1982; Altshuler & Luberoff, 2003; Baum-Snow & Kahn, 2000 and 2005). Indeed, we find linear guideway miles to be the single best predictor of capital costs for the 59 projects. However, we find no statistically relevant correlation between cost per mile and estimates of cost per rider.[3] Figure 1 shows the wide range in capital cost per rider for light rail, despite fairly consistent cost-per-mile measures. By contrast heavy rail has wider ranges in terms of cost per mile, but tight cost-per-rider measures. Some BRT investments, such as the Eugene EmX, recorded low capital costs per mile with as much as half of capital costs going to the purchase of buses. Parts of the Boston Silver Line Phase 1, on the other hand, registered the high capital costs associated with expensive tunneling in a dense downtown.

While capital cost per guideway mile is an effective metric for normalizing costs across projects, it fails to account for the strong positive relationship between capital costs and ridership. Projects in Los Angeles, for example, tend to have high costs per mile but below-average costs per rider, while projects in San Jose have low costs per mile, but among the highest costs per rider. That said, capital cost per annual rider has its own limitations. Most importantly, corridors with high ridership tend to have high ridership regardless of transit technology. As Taylor et al. (2009) observe, some bus lines on Wilshire Boulevard in LA carry more passengers than the city's light rail lines.

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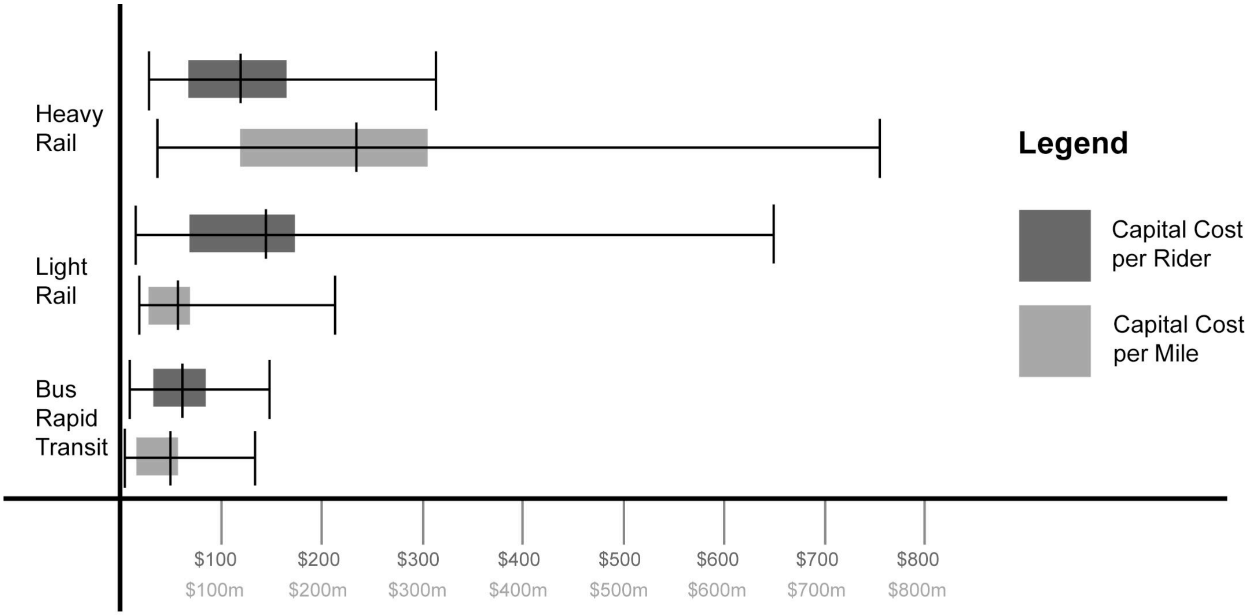
[3] A binomial OLS comparison yields a correlation of .123 and an R-square of .015 at a p value of .354.

Figure 1. Whisker Plot Capital Cost per Rider and Capital Cost per Mile by Mode



Capital Cost and Ridership Models

To investigate the relationship between density, ridership, and capital costs, log-log ordinary least squares (OLS) regressions were estimated to predict ridership (Table 4) and capital cost (Table 5). A cost-per-mile regression was also conducted but has been excluded, since it adds little interpretive value to the capital cost model, which controls for guideway length by mode. Besides providing the best statistical fits, log-log models produce coefficients that represent point elasticities, revealing the percentage change in cost per mile or rider as a function of a one percent increase in density, holding the influences of other predictors constant.

As aggregate-level models, candidate variables for entering the model were related to the following metrics: fixed guideway size and scale (guideway length, number of stations); population and employment densities within ½-mile rings of stations in a corridor; alignment design (percent subway); park-and-ride supplies; metropolitan population size; and fixed-effect dummies (i.e., type of technology; urban area). Variables entered the model if they yielded statistically significant and interpretable results and were free of multicollinearity problems. Residual plots were generated to ensure estimated models did not violate underlying assumptions of OLS estimation.

Ridership (Table 4) was estimated as a function of the number of stations in a project, train frequency, rail technology, parking, jobs density, population density[4], total regional population, and a 0-1 coded city dummy. Controlling for the other variables, heavy-rail enjoyed a ridership bonus, whereas BRT systems typically had fewer riders. The number of stations, density, and parking all had a positive influence on ridership. Variation in capital costs (Table 5) was best explained by total route miles, mode, the percent of project below grade, job density, population density, and a city dummy. Longer, heavy rail, and underground projects all tended to be more expensive.

Table 4. Log-Log OLS Estimating Projects' Average Weekday Ridership

	B	Std. Error	Beta	t	Sig.
(Constant)	2.617	0.788		3.322	0.002
Log of Number of Stations	0.665	0.078	0.428	8.538	0.000
Log of Train Frequency	0.607	0.139	0.254	4.382	0.000
Log of Population per Acre	0.266	0.079	0.162	3.385	0.001
Log of Jobs per Acre	0.281	0.055	0.241	5.111	0.000
Log of Parking	0.091	0.019	0.217	4.862	0.000
Log of Regional Population	0.159	0.057	0.135	2.772	0.008
Heavy Rail = 1	0.532	0.138	0.222	3.849	0.000
Bus Rapid Transit = 1	-0.580	0.175	-0.126	-3.308	0.002
San Jose = 1	-0.970	0.154	-0.233	-6.295	0.000
Northern NJ = 1	-0.490	0.274	-0.076	-1.789	0.080
Baltimore = 1	-0.417	0.189	-0.079	-2.203	0.033
Chicago = 1	-0.588	0.233	-0.092	-2.528	0.015

a Dependent Variable: Log of Average Weekday Ridership
b Adjusted R Square = 0.935 | N = 59

As discussed earlier, our chief interest lies in the relationships between urban densities and both ridership and capital costs. Controlling for other factors, population and job density weree positively correlated with both. As density increases, so do capital costs and ridership. Holding all else constant, a 10% increase in population density corresponds to a 2.66% and 2.60% increase in ridership and capital costs respectively. These elasticities between densities and transit demand are fairly consistent with those found in the meta-analysis by Ewing and Cervero (2010). The capital cost models revealed elasticities of a similar magnitude. From Table 5, a 10% increase in job density corresponds with a 2.81% increase in ridership and 1.77% in capital costs.

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[4] Our analyses were based on gross density measures for two primary reasons. First, gross density normalizes population and employment across the wide range of corridor lengths and thereby eliminates the multicollinearity of jobs, population, number of stations, and route miles increasing in lockstep with corridor size. Second, no secondary national-level database was available for netting out non-residential land areas for the 59 corridors that were studied. The Center for Transit Oriented Development (2006) provides estimates of the percent of land around a transit station that is residential. For the stations areas in our study, the average percent of residential to gross land percentage was 64% with a standard deviation of 27%. Some corridors, particularly in downtown locations, had far lower percentages.

Table 5. Log-Log OLS Estimating Project Capital Costs

	B	Std. Error	Beta	t	Sig.
(Constant)	10.113	.844		11.977	.000
Log of BRT Route Miles	.542	.108	.805	5.024	.000
Log of LRT Route Miles	.635	.090	2.028	7.023	.000
Log of HR Route Miles	.771	.095	2.292	8.138	.000
Log of Percent Subway	.032	.015	.181	2.185	.034
Log of Population per Acre	.260	.110	.168	2.363	.022
Log of Jobs per Acre	.177	.082	.160	2.165	.035
Sacramento = 1	-.758	.295	-.173	-2.568	.013
Chicago = 1	-.873	.413	-.144	-2.111	.040

a Dependent Variable: Log of Capital Costs
b Adjusted R Square = 0.771 | N = 59

Capital Cost per Rider Model

Perhaps more revealing than individual ridership and cost models is a joint model that combines these two metrics. We thus estimated a third log-log OLS model using cost per rider as the dependent variable and including the significant independent variables from the previous ridership and capital cost models (Table 6). This model provides statistically less robust fits (adjusted R Square = .565) than the previous two models – unsurprising given the interaction of variables that are positively correlated with both ridership and capital costs – but provides useful insight into which independent variables have a stronger relationship to one or the other core outcome variables -- ridership and capital cost. We find that both population and jobs per acre have an inverse relationship to capital cost per rider, suggesting that higher densities do tend to improve transit's cost effectiveness, despite higher costs. Some of this benefit is offset by the tendency to switch to heavy rail systems in denser areas. From the elasticity coefficients, we can infer that a 10% increase in population per acre and jobs per acre corresponds with a 3.2% and 1.5% decrease in cost per rider respectively. Other factors contributing to demand for transit, such as number of parking spots and train frequencies, also correlate lower costs per rider. Like density, heavy rail is associated with higher ridership (Table 4) and higher capital costs (Table 5). The relationship with cost per rider, however, moves in the opposite direction as density. Heavy rail projects tend to be more expensive on a cost per rider basis when controlling for population and job density, parking supply, and the share of alignment devoted to subway. Underground alignments tend drive up the cost per rider.

One of the strongest correlates of high capital costs per rider is whether the transit corridor is in a metropolitan area's primary urban area. Projects in San Jose, Trenton, Jersey City and Newark had far higher cost per rider levels than what the model would otherwise predict. We suspect that this relates to the relative costs of auto-travel in these cities, but it may also relate to unobserved city-specific or perhaps even cultural factors. Rather than including a single dummy variable for transit projects outside of the primary urban area, the cities are included as fixed-effect dummy variables. Controlling for regional population, larger cities tend to have higher costs per rider, although this variable was not significant in the capital cost model and was associated with higher ridership.

Table 6. Log-Log OLS Estimating Log of Projects' Cost per Annual Rider

	B	Std. Error	Beta	t	Sig.
(Constant)	1.711	1.726		0.991	0.327
Heavy Rail = 1	0.476	0.195	0.288	2.436	0.019
Log of Percent Subway	0.038	0.014	0.292	2.729	0.009
Log of Train Frequency	-0.519	0.212	-0.315	-2.449	0.018
Log of Parking	-0.051	0.030	-0.175	-1.689	0.098
Log of Population per Acre	-0.321	0.134	-0.285	-2.393	0.021
Log of Jobs per Acre	-0.154	0.085	-0.192	-1.810	0.077
Log of Regional Population	0.366	0.120	0.453	3.053	0.004
San Jose = 1	1.444	0.278	0.504	5.187	0.000
Trenton = 1	3.009	0.679	0.486	4.431	0.000
Northern New Jersey = 1	2.073	0.531	0.470	3.900	0.000

a Dependent Variable: Log of Cost per Rider
b Adjusted R Square = 0.565 | N = 59

Toward a Normative TOD Density

Elasticities and regression results are fine in their own right but are not always useful to practitioners seeking to zone land along existing or planned transit corridors. How can a land-use planner use the finding that every 10 percent increase in population density is associated with a 3.2 percent decrease in cost per rider? More useful to planners and elected officials are benchmarks that can be used in setting minimum densities necessary to support cost-effective transit services.

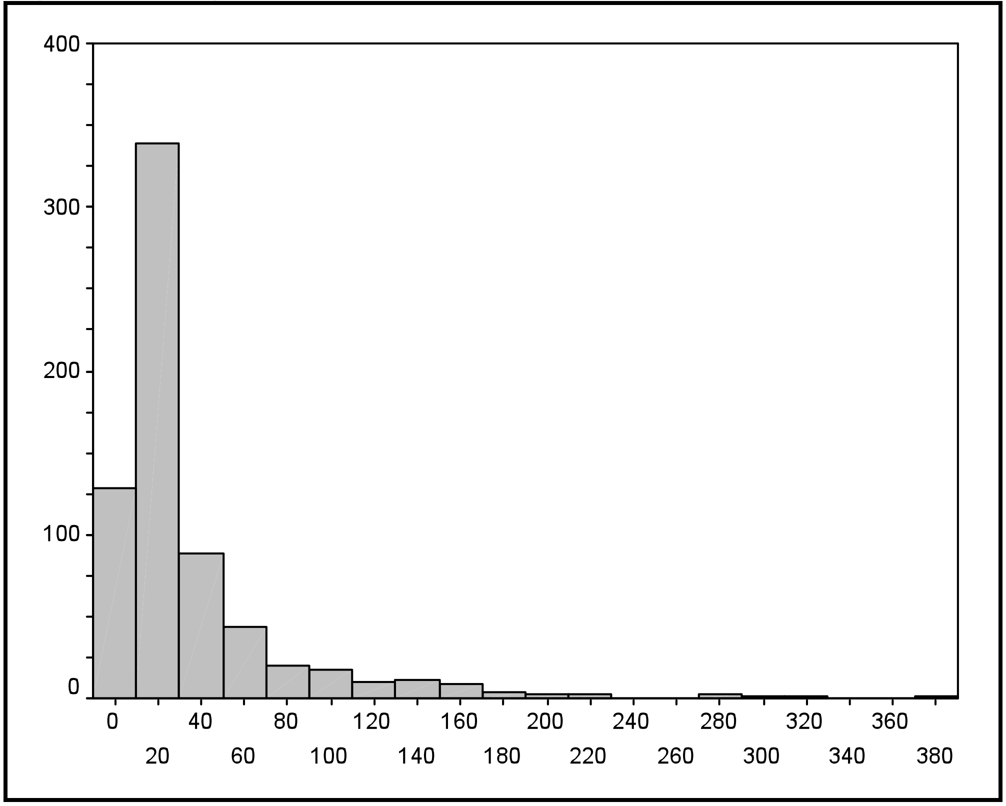
How do the projects we studied compare to the standards set by Pushkarev and Zupan (1977)? Table 7 summarizes urban densities for the 59 projects. The majority of sampled transit stations in the 59 corridors studied had fewer than 19 jobs and persons per acre within a half mile of stations. The higher averages are driven by the dense downtowns of Washington DC, San Francisco, Chicago, Portland and Minneapolis, revealed by the outliers in the histogram in Figure 2. Assuming the average gross-to-net-residential ratio of 67% (Center for Transit Oriented Development, 2006), more than half of stations have lower fewer than 12 acres per net-residential acre, fewer than recommended by

Pushkarev and Zupan (1977) for light rail. If there is an optimal density in terms of "bang for the buck", most transit-station areas are significantly short of it.

Table 7. Transit Station Area Densities

	Average	Std. Dev.	Median
Households per Acre	4.82	4.81	3.74
Population per Acre	10.89	10.82	8.38
Jobs per Acre	23.92	41.51	8.15
Jobs and Population per Acre	34.82	43.72	18.68

Figure 2. Histogram Distribution of Jobs and Population per Acre



One way to infer density thresholds needed to support transit investments is to look for inflection points in cost curves. Figure 3 attempts to do this by holding variables contributing to the cost per rider regression constant at their average and adjusting jobs and population per acre to reveal their influences on capital cost per rider. Figure 4 applies the same equation, but regresses 5th percentile increments of jobs and population density for LRT and HR systems. A noticeable shift in the slope occurs around the 35th percentile. That is, the cost per rider starts shooting up markedly at about the

35th percentile of combined population and employment densities among project in the database. This "inflection point" corresponds to around 27 jobs and persons per gross acre for heavy rail systems and 14 for light rail, suggesting a bare-minimum threshold. Below these levels, the average transit investment is unlikely to approach the ridership levels needed to justify the capital costs.

While the statistical analyses and sensitivity plots provide useful insight into the relationship between densities and capital costs per rider, the models only explain around half of the variation in cost data. Project-specific factors contribute greatly to variations in project costs, in particular. Many policy makers want to know the kinds of densities they should zone for around transit stations under specific conditions or for particular types of transit technologies they can afford. After all, an expensive investment requires greater ridership than a less expensive one and a less dense area will only be able to support smaller capital investments.

Figure 3. Regression Curve of Cost per Rider and Densities

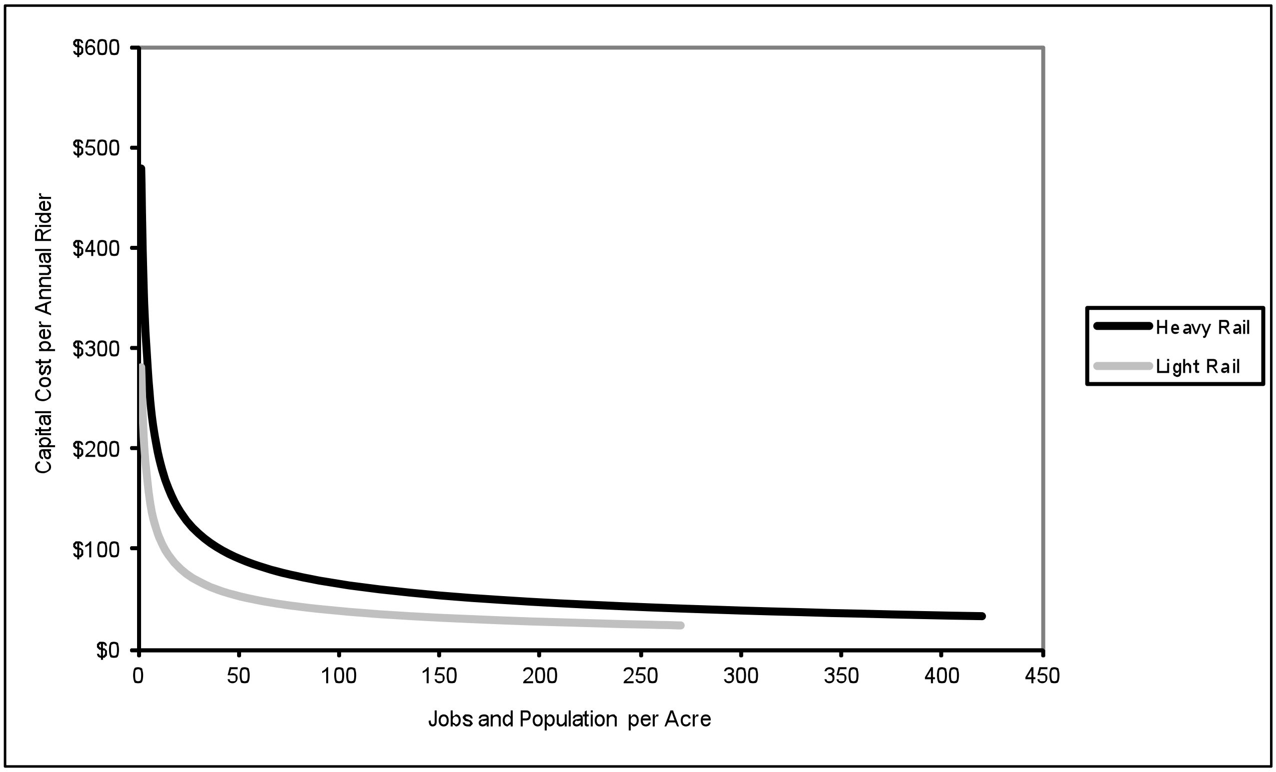


Figure 4. Regression Curve of Capital Cost per Rider and Densities by Density Percentiles

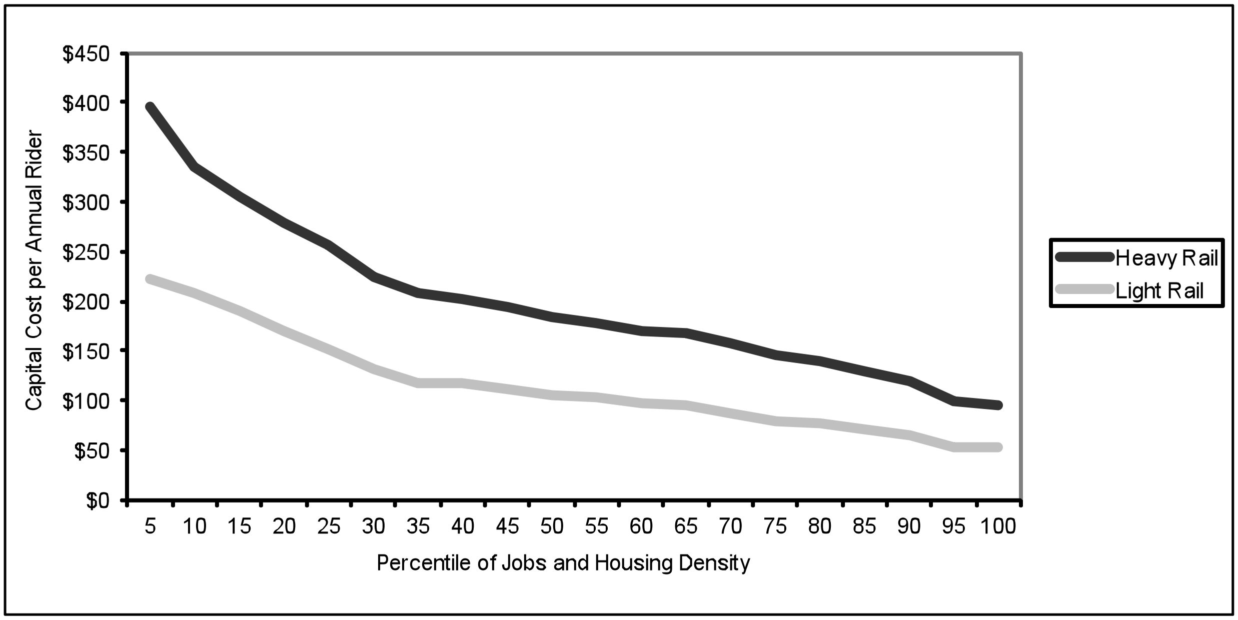


Table 8 looks at the densities needed to achieve a strong cost-per-rider level – assumed to be investments that perform in the top 25th percentile of the 59 projects – given different capital costs per mile. Density estimates are excluded for light rail projects costing less than $10 million and heavy rail below $20 million per mile, since these costs are well below observed costs. The ridership regression equation from Table 4 provides the basis for estimates while holding other variables – parking, train frequency, regional population, number of stations, and track miles – constant at their averages as well as one standard deviation above and below the average.[5] In generating the estimates, it is assumed there are twice as many jobs as people (the average corridor had 23 jobs and 11 people per gross acre). Given the similar elasticities of job and population densities to ridership, however, the distribution between the two is flexible (assuming twice as many people as jobs per gross acre would provide similar, though lower, estimates).

According to the estimates, an average light rail system in an average city requires approximately 56 jobs and persons per gross acre in order achieve a strong cost-per-rider performance with an average capital cost of $50 million per mile. Corridors with other desirable features may perform well despite low densities. For example, despite having fewer than 10 jobs and residents per acre, the Franconia/Springfield extension in Washington DC averaged a low cost per rider, owing in part to its low capital costs per mile, plentiful supply of parking, frequent train service, and location

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[5] At one standard deviation below the average, parking per station is below zero. We therefore assume no parking for investments that are one standard deviation below the average.

within a large metropolitan region with good transit service. The capital costs of the best performing projects (25th percentile) range from $6 million to $200 million per mile.

Table 8. Setting Norms: Transit Station Area Densities related to Capital Costs per Mile

Normative Jobs and Population Density Thresholds for Fixed Guideway given Specified Cost per Mile and 25th Percentile Cost/Rider Performance (Target = $66.54)

Millions/Guideway Mile	$5	$10	$25	$50	$75	$100	$150	$200	$250	$300
LRT										
Std Dev Below	-	7	35	125	-	-	-	-	-	-
Average System	-	3	16	56	116	-	-	-	-	-
Std Dev Above	-	1	5	17	35	59	122	-	-	-
HR										
Std Dev Below	-	-	14	47	98	167	-	-	-	-
Average System	-	-	12	41	76	146	-	-	-	-
Std Dev Above	-	-	2	6	14	22	47	79	118	164
BRT										
Std Dev Below	5	20	101	360	-	-	-	-	-	-
Average System	2	17	88	312	-	-	-	-	-	-
Std Dev Above	1	3	14	47	100	169	-	-	-	-

Caveats and Next Steps

Any transit-supportive density threshold should be approached with caution and perhaps even a healthy dose of skepticism. Although they share similarities, each transit system and project is unique with its own set of extenuating circumstances and particularities. Furthermore, each system has observable, as well as unobservable, variations that influence ridership. There is no one or even dozen hard and fast density thresholds that can be applied across all projects. Furthermore, even if a normative acceptable cost recovery figure could be established, it would probably vary in different locations. High-cost per rider figure in some areas may be offset by higher congestion reduction benefits, contributions to downtown economies of scale, and more expensive next-best alternatives. Should transit in an area with low parking and driving costs be valued by the same criteria as transit in highly congested and expensive areas? Despite these caveats, advancing new threshold measures contributes to the discussion of how cities and towns can zone to encourage transit. At least as a first-cut analysis, any municipality can position itself at an appropriate point in the graph of Figure 3 or in a cell of Table 8 to infer the kinds of densities that might be needed to support a proposed or existing transit investment.

The next step in our analysis is to incorporate refined station-level ridership estimates, that account for bus connections, network attributes, distance to downtown, CBD size, and relative auto costs, into Table 8. We also hope to refine the regression, using Structural Equation Modeling, which was not advisable with only 59 cases, to address the interactions between independent variables. For example, train frequency is found to have a positive correlation with ridership, but the nature and the directional strength of the relationship is not entirely understood. Train frequency increases the attractiveness of transit and hence ridership, but it also responds to demand: agencies run trains frequently where ridership is high. Agencies are also less likely to provide park-and-ride facilities in dense downtown areas. After refining the model, we aim to create an online tool, where transit and planning agencies can enter variables associated with a proposed alignment into a spreadsheet that will then provide a summary of minimum zoning recommendations by average cost per mile of the alignment.

Conclusions

The results of Pushkarev and Zupan's work from a third of a century ago are still often used to guide land-use planning and zoning in high-capacity transit corridors. This is despite their work being drawn from a limited number of rail investments mostly in the northeast and the availability of cost and ridership data for newer generation projects built over the past several decades. While data from these projects have limitations as well, we believe the empirical results presented in this paper help to refine past findings and offer new insights that can help in setting benchmarks for zoning land around existing and future transit stations.

At a time when fiscal resources are shrinking and capital investment costs are soaring, rail transit has become a lightning rod for political controversy and infighting. Critics consider rail proposals to be among the most flagrant forms of pork barrel politics today. Advocates counter-argue that aggressively expanding the nation's rail transit offerings will yield many under-appreciated environmental and societal benefits over the long run, not the least of which are reduced carbon emission and dependency on foreign oil supplies.

What is less debatable is the reality that if fixed-guideway transit is to yield appreciable dividends, there must be a close correspondence between transit investments and urban development patterns. All too often, rail transit investments in the U.S. have been followed by the majority of growth being oriented to highway rather than transit corridors (Cervero and Landis, 1992; Cervero et al., 2004). Successful transit-oriented development requires pro-active government involvement, which includes zoning for the densities needed to sustain cost-effective transit services. While higher density areas tend to have higher transit capital costs as well as higher ridership, our analysis suggests that many transit stations in the US do not have the surrounding job or population densities to support cost-effective transit service. We suspect these barriers are more regulatory than market-driven and that restrictive zoning is a major obstacle to increased transit efficiency. The thresholds presented in Table 8 can hopefully provide cities and towns a point of comparison and a potential target for zoning around existing and proposed transit stations based on actual or projected costs.

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