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Michael Duncan[1]

Abstract

Rail transit systems often provide park-and-ride facilities as a way for passengers to access stations. Using the land around stations for development rather than parking would allow more passengers to access the system without driving and ostensibly go much further toward reducing dependence on automobiles. However, it is unclear whether ridership levels can be maintained without a park-and-ride option. This research seeks to illuminate this issue with a demand model for the Bay Area Rapid Transit (BART) system. Passenger counts are estimated for each origin/destination pair in the BART system based on such variables as parking spaces, housing units, and employment adjacent to stations. Parameters from this model are then used to estimate the amount of development required to replace the riders generated by station parking. Depending on the characteristics of a station and its spatial relationship with other stations, the level of development density required to effectively replace parking is found to be much higher than what is generally feasible.

Keywords

rail, transit, park-and-ride, TOD, transportation planning, sustainability, hierarchical model

In the past two decades, many in the planning community (academics and practitioners alike) have advocated transit-oriented development (TOD) as an important tool in reducing dependence on automobiles and, thus, improving the sustainability of the transportation system (Dittmar and Ohland 2004; Transit Cooperative Research Program [TCRP] 2004; Bernick and Cervero 1997). TOD is commonly defined as compact and mixed-use development surrounding a transit station (typically a rail station). Such development provides good pedestrian access to stations as well as generally promoting pedestrian activity. Given the positive rhetoric surrounding TOD, one might find it surprising that the land adjacent to stations is frequently used for park-and-ride facilities[1] rather than TOD. The prominence of these parking facilities may stem from a variety of factors, but a major reason lies in their ability (real or perceived) to facilitate greater usage of a transit system. To the degree that transit operators feel they can use parking to maximize ridership, parking will likely form a persistent barrier to TOD. Furthermore, if parking provides the most realistic way to attract riders, it raises questions as to whether replacing parking with TOD would be the most sustainable strategy.

This research analyzes ridership patterns on the Bay Area Rapid Transit (BART) system in an effort to gain a better understanding of the trade-offs involved in using the scarce land adjacent to stations for parking or development. BART was chosen as the subject of this analysis for two primary reasons: (1) BART is an extensive rail system with a relatively large and diverse set of stations, and this allows for an evaluation of how different station environments can influence ridership. (2) BART is one of a handful of rail systems that systematically collect passenger counts for each unique origin-destination pair of stations, and this type of data provides certain advantages in modeling ridership.

A hierarchical regression model that predicts ridership for each BART station pair represents the primary empirical contribution of this article. The resulting coefficients of this model are used to predict the decrease in BART ridership that would occur with the removal of a park-and-ride facility and how much new development (residential or nonresidential) would be needed to offset this ridership loss.[2] For most BART park-and-ride stations, the model indicates that more than one new housing unit or job[3] must be placed adjacent to the station for every parking space that is removed. This translates to more than one hundred units or jobs per acre. As with most U.S. cities, such densities infrequently occur in the Bay Area except in the urban core (San Francisco and Oakland). As the majority of BART stations extend outside of this core,

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these results suggest that the provision of station parking usually represents the most practical way to maximize ridership. If replacing parking facilities with TOD results in ridership losses, it will prove difficult for a transit operator to adopt such a strategy. This does not necessarily mean that parking replacement is the wrong strategy, but it will likely require a broad justification that goes beyond a singular focus of ridership.

Research Context

Sustainable Transport and TOD

Urban planners have long been concerned with the environmental and social sustainability of cities and regions (Wheeler 2004; Campbell 1996). A big part of this concern revolves around transport systems. The auto-based transport system found in most U.S. cities (and, to a lesser degree, other developed countries) has many elements that are not environmentally and socially sustainable (Richardson 1999; Murphy and Delucchi 1998). These undesirable elements include high vehicle emissions, consumption of imported petroleum, traffic fatalities and injuries, congestion, exclusion of those who cannot drive for physical or economic reasons, reduced levels of physical activity, and sprawl. Strategies to redress these problems fall into two broad categories (Richardson 2005): (1) increasing the sustainability of auto use and (2) reducing dependence on automobiles. The former strategy relates to the production of cheaper and safer vehicles that use clean, renewable, and widely available energy sources. The responsibility for moving this work forward largely falls on engineers, scientists, and the policy makers who have the power to incentivize innovation. As such, planners interested in sustainable transport mainly focus on the second strategy of reducing automobile dependence through the design and integration of transportation and land use systems (Jun 2008; Boarnet and Crane 2001; Banister, Watson, and Wood 1997).

The movement to improve sustainability through decreased auto usage explains the strong appeal of TOD to planners. The combination of good transit and pedestrian access inherent in TOD provides a relatively complete alternative to auto travel. A handful of recent studies have empirically illustrated that TOD can reduce auto dependence among those who live or work in a TOD[4] (TCRP 2008; Cervero 2007; Chatman 2003).

While TOD may significantly reduce individual or household level auto usage, achieving measurable sustainability benefits at a regional level will require a large expansion of TOD. However, in most U.S. regions, such an expansion presents a strong challenge (Downs 1994). Many of the barriers to TOD are those that apply more generally to high-density and mixed-use development: restrictive land use policy, lack of demand, and unwillingness of developers and lenders to take on nonconventional projects (Levine 2005; TCRP 2004). A challenge more specific to TOD is the inherent limit on the supply of land adjacent to transit stations and the fact that park-and-ride facilities occupy much of this land. The provision of parking can sometimes be symptomatic of the other development barriers (e.g., if local zoning prevents high-density development, a transit operator will have little incentive to do anything other than build a parking lot). However, in locations with permissive development regulations, parking facilities can themselves create the primary barrier to station area development.

Advantages of Park-and-Ride

The general auto-orientation of most U.S. cities means that providing park-and-ride facilities can maximize the number of people who can easily get to stations (Shirgaokar and Deakin 2005; Merriman 1998). A parking facility extends the radius of a station's catchment area by several miles, and this causes an exponential expansion of the land area and population served by a given station.[5] For example, according to the 2000 U.S. census, there were roughly one hundred thousand Bay Area households within a ten-minute walk (a half mile) of a BART station, while there were nearly 1 million households within a ten-minute drive (3.5 miles). This enlarged catchment has both operational and political advantages.

From a political perspective, a large catchment area ensures that a greater number of the taxpayers who subsidize a public transit system have access to it. This may prove politically advantageous even if most people never actually use the transit system. The idea of having an even spatial distribution of transport services, however inefficient, has been termed "geographic equity" (Taylor 1991). While not the focus of this research, examining the degree to which the pursuit of geographic equity influences the provision of station parking presents an interesting avenue for future research.

From an operational perspective, transit agencies are concerned with how parking might affect ridership and fare revenue.[6] If station parking ensures that the maximum number of people have easy access to stations, this seems likely to increase ridership. Park-and-ride also provides a quick and reliable base of potential riders as compared to TOD, which might take many years to reach full fruition. Furthermore, if the provision of parking can attract a significant number of riders who would not otherwise use transit, one might argue that this provides a pragmatic compromise with regard to sustainability. A short auto trip to and from a rail station will have fewer social costs than a longer trip to and from the final destination.

To some degree, the argument that station parking can maximize ridership seems to contradict claims that increased ridership is a benefit of TOD (TCRP 2008, 2004). Research has regularly demonstrated that proximity to a transit station increases the likelihood of using transit, and TOD obviously puts more people in close proximity to a station (Cervero 2007; TCRP 1996). However, assuming realistic development densities, relatively few people can live near a station. Because of the larger catchment of a park-and-ride station, ridership can remain high even if the average individual in that catchment area lives far from the station and has a small likelihood of using transit. In other words, a large service area population with a low individual rate of transit usage may produce more riders than a small service area population with a high individual rate of usage.

Disadvantages of Park-and-Ride

While the provision of station parking may represent a rational approach for a transit operator trying to maximize usage of its facilities, this accepts the status quo of an auto-orientated transport system. As such, park-and-ride lots can compromise sustainability goals in a variety of ways (Parkhurst 1995):

- Park-and-ride spaces will not improve transport options for those who cannot drive due to physical or financial limitations.[7] The growth of the elderly population in the United States will make this an increasingly important consideration (Dumbaugh 2008).
- If a car is required to reach a station, it does not reduce a household's incentive to own an automobile. This may have a spillover effect by increasing the likelihood that people will drive for trips that the rail system does not accommodate.
- Parking lots can create a dangerous and unpleasant environment for pedestrians and deter those who would otherwise access the transit system by nonmotorized modes (Pucher and Dijkstra 2003).
- Emissions per vehicle mile traveled (VMT) decrease with trip distance[8] (Kessler and Schroeer 1995). Fuel efficiency also decreases with trip distance (Jensen 1995). As such, when someone reduces his or her VMT by using park-and-ride transit, it does not cause a proportional reduction in emissions and fuel consumption.
- By using the land that would otherwise be optimal for TOD, the provision of station parking can compromise the potential for development impacts, which are frequently used to justify the large cost of rail investment[9] (Litman 2007; Cervero and Landis 1997; Knight and Trygg 1977). Parking can also weaken station area impacts by extending the geographic range of the station catchment area and, thus, weakening economic incentives to focus development around stations (Giuliano 2004).

Ridership as the Outcome of Interest

Ridership alone does not fully justify the provision of park-and-ride facilities. Many other factors require consideration, including the opportunity cost of the land used for parking and the various sustainability concerns discussed above. Replacing station parking with development may prove the optimal strategy from a broad cost-benefit perspective, even if this means losing riders. Nonetheless, as long as parking promotes greater transit usage, making an argument for its removal will prove difficult. The benefits of TOD are likely to be less tangible and more difficult to measure than passenger counts. Even if an objective cost-benefit analysis clearly illustrated the provision of parking as an inferior strategy, it would prove difficult to convince a transit operator to forgo ridership (and the associated fare revenue) in favor of broader sustainability goals. Transit agencies frequently acknowledge sustainability as a critical aspect of the service they provide (American Public Transportation Association [APTA] 2010; Federal Transit Administration [FTA] 2010; BART 2008). However, such acknowledgments likely flow from an assumption that increased transit usage coincides with improved sustainability.

While increased ridership may not completely justify the provision of station parking, it provides a necessary component of a good justification. If, on the other hand, replacing parking with development can be shown to increase or, at least, maintain ridership, the justification for the provision of station parking is weak (notwithstanding the geographic equity issue mentioned earlier). Thus, there is a clear need to have a good understanding of how parking and development impact ridership. Certainly, some amount of development would fully replace the number of passengers generated by a parking facility. The problem then becomes determining whether the required development density is feasible given the political and market conditions in the area surrounding a given station. The following ridership model attempts to estimate a density threshold at which residential and commercial development can effectively replace the ridership generated by a park-and-ride facility.

Research Methodology

Direct Demand Model of Origin-Destination Station Pairs

Researchers have frequently examined rail ridership from the perspective of individual mode choice (Cervero 2007; TCRP 1996; Frank and Pivo 1994). Such studies indicate that living or working in close proximity to a station increases the probability of choosing rail for a given trip. However, this kind of analysis makes it difficult to accurately measure aggregate demand for any particular segment of a rail network. Since the question this research seeks to answer fundamentally focuses on aggregate ridership, my analysis will model aggregate rider counts (i.e., a "direct demand" model is estimated). Analysis of aggregate data has a major drawback in that it obscures the various individual characteristics that influence travel behavior. However, modeling aggregate rider counts likely provides the most direct and feasible approach to accurately addressing the research question. A detailed discussion and justification of using aggregate data is provided in the appendix.

There is a history of using direct demand models to measure station level ridership (Lane, Dicarlantonio, and Usvyat 2006; BART 2006; Kuby, Barranda, and Upchurch 2004; TCRP 1996). This analysis seeks to advance the methodology of these studies by analyzing passenger counts for each unique origin-destination (OD) station pair, rather than analyzing total passenger counts at a particular station. This OD approach has two main advantages:

1. Using OD pairs allows the model to better account for the three main factors that theoretically determine transit usage: whether an origin station has attributes that produce trips, whether a destination station has attributes that attract trips, and the service quality between stations (relative to other travel options). When analyzing aggregate boardings at a particular station, one cannot accurately measure destination attributes or service quality because the people boarding at that station will have a variety of destinations. Previous work has partially addressed this problem by using a composite measure of the attractiveness of all potential destination stations (e.g., a weighted sum of activities at potential destinations, with the more proximate destinations being weighted more heavily) (BART 2006; Kuby, Barranda, and Upchurch 2004). However, using OD pairs as the unit of analysis allows a much more precise specification of service quality and destination station characteristics.
2. By analyzing OD pairs, the number of observations greatly increases. At the time the ridership data used in this study were collected, there were thirty-nine BART stations.[10] Figure 1 presents a map of the BART system. This limited number of observation sites makes it very difficult to estimate a demand model with statistically significant coefficients (BART 2006). Conversely, a thirty-nine-station system has 1,482 OD pairs, which obviously allows for more robust statistical inference.

OD data are relatively rare. Accurate OD counts require a fare collection system that tracks both the entrance and exit station for each passenger. Only BART and few other U.S. rail operators (e.g., Washington D.C. Metro, MARTA in Atlanta) have this type of system in place. The passenger count data used in this analysis come directly from BART's automated fare collection system. BART uses a software program that records the origin station, destination station, day, and time for each passenger and places this information in a database. For the subsequently presented model, average weekday passenger counts for 2002 were extracted from the BART ridership database and used as the dependent variable. Data from 2002 were the earliest available and were chosen because they most closely match with the 2000 census data, which are used to measure the amount of station area development.

Model Specification

This analysis utilizes a hierarchical (or multilevel) model, which effectively and accurately accommodates the nested structure of OD data[11] (Raudenbush and Bryk 2002). Each OD pair in this analysis nests into two sets of observations. The first set includes all the other OD pairs that have the same origin station, and the second set is made up of OD pairs with the same destination station. Thus, a cross-classified hierarchical model[12] was specified as follows:

- Dependent variable: OD specific passenger count.
- Lower-level predictors: OD specific service characteristics.
- Upper-level predictors (class 1): origin station attributes and a random effects term capturing the variation in ridership that can be attributed to the origin station but is not captured by the specified origin station attributes.
- Upper-level predictors (class 2): destination station attributes and a random effects term capturing the variation in ridership that can be attributed to the destination station but is not captured by the specified destination station attributes.
- Interactions: interactions between service characteristics and origin station attributes, between service characteristics and destination station attributes, between origin station attributes and destination station attributes, and between two origin station attributes.[13]

A natural log transformation was applied to the dependent variable. The previously cited research that makes use of a direct demand model is mixed in terms of the functional form, leaving no clear precedent in this regard. For this analysis, the log transformation serves well for a few different purposes. First, it serves to correct the positively skewed distribution of the OD passenger counts[14] that can otherwise lead to flawed statistical inference (i.e., biased standard errors). The transformation also ensures that the model does not predict negative rider counts.[15] Transforming the dependent variable also allows the origin station attributes, destination station attributes, and service characteristics to have a multiplicative rather than additive influence on ridership, which seems theoretically appropriate (Kuby, Barranda, and Upchurch 2004). For example, a given OD station pair may have a low fare, frequent service, and a fast travel speed, but this will not guarantee high ridership if the origin station lacks trip

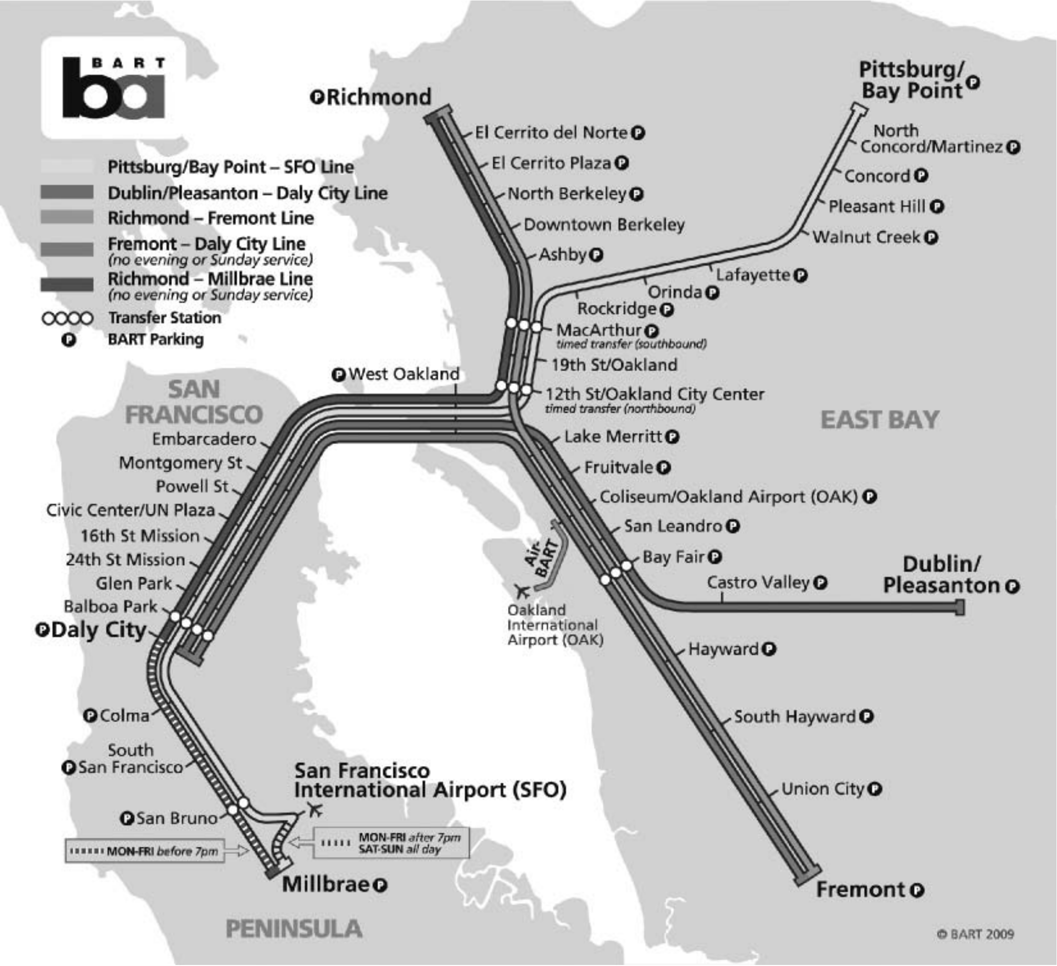

Figure 1. BART system map
Source: Bay Area Rapid Transit System (BART; 2009).

producing activity or the destination station lacks attractions. An additive model would wrongly predict that a given service quality improvement would always add a fixed number of new riders (independent of station characteristics). A multiplicative model would more appropriately predict that the service improvement would multiply the existing ridership and, thus, the number of new riders will depend on station characteristics. Logarithmic transformations were also applied to all of the continuous independent variables. Nearly all of these variables were found to have a stronger statistical relationship with ridership after this transformation.[16]

Home-Origin Passengers

The passenger counts used as the dependent variable include an estimation of only those passengers for whom the origin station is the home end of the trip. Such passengers will be subsequently referred to as "home-origin passengers." Because the mechanically collected ridership data do not indicate whether a passenger is coming from home, the mechanical counts were merged with survey data using an iterative proportional fitting procedure (IPF)[17] (described in the appendix). Despite the methodological complication caused by focusing on home-origin passengers, this approach was chosen because it allows for a simple and clean model specification. Origin station variables need only include characteristics that would allow someone to reach the BART station from her or his home (e.g., parking spaces and nearby housing), and destination station variables need only include characteristics that would cause riders to exit at a station (e.g., nearby employment).[18]

The IPF procedure used to calculate home-origin passengers will produce some error, which raises concerns about how this might affect model results. To test how the choice of dependent variable impacts the accuracy of model predictions, a model using the unaltered total passenger counts was estimated and tested against a model using home-origin passengers (this testing is also described in the appendix). This testing indicated that, despite the fact that the home-origin rider counts were not precisely measured, using such counts increased the overall accuracy of ridership predictions. While a positive sign, this does not rule out the potential that the imputed dependent variable might create biased coefficients or standard errors. As such, the model parameters should be interpreted with caution.

Variable Descriptions

Tables 1 and 2 present descriptions and summary statistics, respectively, for the variables used in the model. The OD specific variables are meant to control for the service quality characteristics that theoretically influence ridership: travel time, frequency, cost, and competition from modes other than BART. The origin characteristics mainly[19] measure the ease with which BART passengers can get from their home to a station using various modes: housing near the station means that people can easily walk to the station, park-and-ride spaces provide an ability to drive to the station, and bus connections obviously allow people to access a station by bus. The destination characteristics primarily measure the ease with which passengers can get from a station to out-of-home destinations. Employment near the station allows people to easily walk from a station to their work place or other nonwork activities,[20] bus connections serve to shuttle people to a wider set of destinations, and sports stadiums represent a large concentrated attraction that is particularly suited to transit.

In addition to the variables included in the final model, other station area characteristics likely to make a station more attractive as an origin or destination were also tested but excluded due to statistical insignificance. These variables include the following:

- Pedestrian connectivity (measured as intersection density) at both the origin and destination station. This variable captures the ease with which one can walk to and from a station.
- The presence of bike storage facilities at the origin station. Bike facilities make it easier for BART passenger to access the station by cycling.
- Socioeconomic characteristics at the origin station (e.g., income, home ownership status, ethnicity of residents). Certain population segments have a greater propensity to use transit, and these variables were tested to control for the different socioeconomic profiles of the population surrounding each station.
- Employment at the destination station broken into different categories (by industry and occupation). These variables were meant to control for the different commercial/industrial profiles at each station.
- Parking cost at the destination station. As parking costs increase, BART should become a more attractive alternative to driving.

The insignificance of these variables likely reflects the fact that this analysis only has thirty-nine stations, and thus, the limited variation in the data only allows for a few variables with statistically significant coefficients. An analysis of a rail system (or multiple systems) with more stations and a broader diversity of station areas would better address relationship between ridership and a larger set of station area attributes. However, the variables included in the model are broadly representative of the development profile around a station and can still provide useful inferences.

The measures of station area housing and employment require some additional description that is not provided in Table 1. This analysis is most interested in the influence of development very near a station that would occur in place of a parking facility. However, to isolate the influence of this very proximate development, the model must also control for more distant development. To accomplish this, a series of variables measuring the amount of development in concentric bands were initially specified (e.g., housing units within 0.1 miles of a station, units between 0.1 and 0.2 miles, units between 0.2 and 0.3 miles, etc.). However, the amount of development in one band is highly correlated with the next band, and this approach led to insignificant coefficients without an interpretable pattern. As an alternative, composite indices of housing and employment were used. These indices include a weighted sum of all housing or employment within 1 mile of a station, with the more proximate development being weighted more heavily. Various distance decay functions were tested as a way to weight these indices. The decay functions used in the final model (as described in Table 1) were selected because they provided the best model fit.

Model Interactions

The model specification includes a series of interactions terms (the product of at least two independent variables). The coefficients for these interactions measure how an independent variable can moderate the influence of another independent variable on the dependent variable. In the case of this analysis, the interactions allow for the testing of how the influence of station attributes on ridership may be moderated by other variables. The motivation for including interactions stems from recent survey research of Bay Area park-and-ride passengers that demonstrated how they generally make long trips to the central business district (Shirgaokar and Deakin 2005). This suggests that the strength of the relationship between station attributes (in this case parking) and transit usage may depend on the specific attributes of an OD pair. This has important implications because it would mean that the amount of development needed to replace parking without losing ridership will vary from station to station.

Multiple interactions involving housing, employment, and/or parking were tested. Each of the interactions that proved statistically significant[21] is described in more detail below (with the expected sign in parentheses):

Table 1. Variable Descriptions

Variable name	Variable description	Source (data year)
Dependent variable		
riders_ho	The number of home-origin weekday riders (averaged from all weekdays in 2002)	Mechanical BART (Bay Area Rapid Transit System) Passenger Counts (2002) and BART Passenger Survey (1999)
Origin-destination (OD) specific predictors		
bart_tt	BART station-to-station travel time	BART (current timetable)
auto_tt/bart_tt	Ratio of A.M. peak auto travel time to BART travel time for the OD pair	BART (current timetable) and Metropolitan Transportation Commission Zone to Zone Travel Times (2000)
freqency16	Binary variable indicating that an OD pair is served by 16 BART trains/hour during the A.M. peak (4 trains/hour is the reference)	BART (current timetable)
freqency12	Binary variable indicating that an OD pair is served by 12 BART trains/hour during the A.M. peak (4 trains/hour is the reference)	BART (current timetable)
freqency8	Binary variable indicating that an OD pair is served by 8 BART trains/hour during the A.M. peak (4 trains/hour is the reference)	BART (current timetable)
transfer1	Binary variable indicating that traveling by BART on this OD pair requires a transfer of trains	BART (current timetable)
transfer2	Binary variable indicating that traveling by BART on this OD pair requires 2 transfers of trains	BART (current timetable)
fare	Required fare payment (BART has a distance based fare system)	BART (2003)
distance	The street network miles between the origin station and destination station	U.S. Census Tiger Data (2000)
muni	Binary variable indicating whether the OD pair is also served by MUNI light rail	San Francisco Municipal Railway (current route maps)
Origin station predictors		
housing_o	Weighted sum of housing units (in thousands) within 1 mile of the origin station.[a] Weighting was based on the proximity of a block to a station using the following exponential decay function: $e^{-(2\times\text{miles to station})}$	U.S. Census (2000), block-level data
parking_o	The number of park-and-ride spaces (in thousands) at the origin station	BART (2000)
bus_o	The number of connecting buses/hour at origin station	BART (2003)
terminal_o	Binary variable indicating the origin is a terminal station (i.e., the last station on a line)	BART (2003)
Destination station predictors		
jobs_d	Weighted sum of jobs (in thousands) within 1 mile of the origin station.[a] Weighting was based on the proximity of a block group to a station using the following exponential decay function: $e^{-(4\times\text{miles to station})}$	U.S. Census (2000), block-group-level data
parking_d	The number of park-and-ride spaces (in thousands) at the destination station	BART (2000)
bus_d	The number of connecting buses/hour at destination station	BART (2003)
terminal_d	Binary variable indicating the destination is a terminal station (i.e., the last station on a line)	BART (2003)
stadium_d	Binary variable indicating that destination station serves the Oakland Coliseum/Oracle Arena	Google map (current)

[a] Housing/employment that was within one mile of more than one station was assigned to the nearest station.

Table 2. Variable Summary Statistics

Variable name	Mean	Standard deviation	Minimum	Maximum
Dependent variable				
riders_ho	81.77	161.66	0.33	1,725.39
Origin-destination (OD) specific predictors (*N* = 1,482)				
bart_tt	31.06	17.11	1.00	85.00
auto_tt/bart_tt	1.30	0.61	0.39	6.28
freqency16 (binary)	0.06	—	—	—
freqency12 (binary)	0.02	—	—	—
freqency8 (binary)	0.34	—	—	—
transfer1 (binary)	0.22	—	—	—
transfer2 (binary)	0.02	—	—	—
fare	2.70	0.99	1.15	4.95
distance	17.54	9.85	0.32	43.95
muni (binary)	0.004	—	—	—
Origin station predictors (*N* = 39)				
housing_o (000's)	2.67	2.02	0.28	9.83
parking_o (000's)	1.00	0.90	0.00	3.34
bus_o	10.95	6.81	2.00	34.00
terminal_o (binary)	0.13	—	—	—
Destination station predictors (*N* = 39)				
jobs_d (000s)	4.17	8.09	0.02	37.14
parking_d (000s)	1.00	0.90	0.00	3.34
bus_d	10.95	6.81	2.00	34.00
terminal_d (binary)	0.13	—	—	—
stadium_d (binary)	0.03	—	—	—

- Origin housing (*housing_o*) × BART travel time (*bart_tt*) (–): One can quickly and easily reach a station when living in close proximity. As the station-to-station travel time increases, access time becomes a smaller share of the trip cost, and this likely reduces the relative value of convenient station access. Consequently, the influence of housing on ridership may decline for OD pairs that are further apart.
- Origin housing (*housing_o*) × origin parking (*parking_o*) (–): Because the presence of parking likely diminishes pedestrian connections to the station, the relationship between housing and ridership may weaken as parking increases.
- Origin parking (*parking_o*) × auto/BART travel time ratio (*auto_tt/bart_tt*) (+): Driving to a station, looking for parking, and then changing modes can be an inconvenience. If BART cannot provide travel times that are competitive with driving, potential park-and-ride passengers (who obviously have access to a vehicle) may just drive to their final destination. Consequently, in congested corridors where BART often travels faster than cars (i.e., the auto/BART travel time ratio is high), parking should have a greater effect on ridership because the lure of simply driving to one's final destination is not as great.
- Origin parking (*parking_o*) × destination employment (*jobs_d*) (+): Park-and-ride passengers are often suburban professionals working in large employment centers (Shirgaokar and Deakin 2005; Black 1995). As such, high levels of employment at the destination may mean that parking at the origin has a stronger influence on ridership.
- Destination employment (*jobs_d*) × BART travel time (*bart_tt*) (+/–): The influence of this interaction on ridership could theoretically be positive or negative. Having employment near the station reduces the time it takes to travel from the station to the final destination. As with housing, this convenient access becomes a small part of the overall trip cost for long trips, suggesting that the influence of destination employment decreases with travel time. On the other hand, people may have a greater willingness to tolerate extra travel time for access to large commercial centers. This holds especially true when considering that the high parking costs in the Bay Area business districts makes BART an especially attractive option. Therefore, the influence of employment on transit usage may become relatively stronger with longer trips. The subsequent analysis provides evidence that the latter is the stronger effect as this interaction is significantly positive.

Table 3. Model Results

Variable name	Coefficient	Standard error	*t*-ratio	*p*-value
Origin-destination (OD) specific predictors (*N* = 1,482)				
ln(bart_tt)	–0.127	0.085	–1.49	0.14
ln(auto_tt/bart_tt)	0.498	0.087	5.70	0.00
freqency16 (binary)	0.778	0.115	6.77	0.00
freqency12 (binary)	0.304	0.120	2.53	0.01
freqency8 (binary)	0.212	0.045	4.69	0.00
transfer1 (binary)	–0.754	0.053	–14.26	0.00
transfer2 (binary)	–1.419	0.137	–10.34	0.00
ln(fare)	–0.768	0.110	–6.99	0.00
1/distance	–1.282	0.119	–10.81	0.00
muni (binary)	–0.983	0.247	–3.98	0.00
Origin station predictors (*N* = 39)				
ln(housing_o) (000s)	0.434	0.136	3.20	0.00
ln(parking_o) (000s)	0.172	0.085	2.03	0.04
ln(bus_o)	0.392	0.080	4.89	0.00
terminal_o (binary)	0.241	0.169	1.43	0.15
Destination station predictors (*N* = 39)				
ln(jobs_d) (000s)	0.232	0.087	2.67	0.01
ln(parking_d) (000s)	–0.168	0.078	–2.16	0.03
ln(bus_d)	0.626	0.125	5.02	0.00
terminal_d (binary)	0.419	0.222	1.89	0.06
stadium_d (binary)	0.975	0.429	2.28	0.02
Interactions				
ln(housing_o) × ln(bart_tt)	–0.071	0.032	–2.26	0.02
ln(housing_o) × ln(parking_o)	–0.119	0.060	–1.96	0.05
ln(parking_o) × ln(auto_tt/bart_tt)	0.144	0.040	3.59	0.00
ln(parking_o) × ln(jobs_d)	0.050	0.008	5.94	0.00
ln(jobs_d) × ln(bart_tt)	0.039	0.016	2.46	0.01
Constant	1.849	0.394	4.70	0.00
Dependent variable: ln(rider_ho)				

Model Results

Basic Description

Table 3 presents the results of the BART demand model. Nearly all of the estimated coefficients are significant and intuitive. Except for parking, housing, and employment, the other variables in this analysis serve largely as controls. As one would expect, the negative coefficients for fares, travel time, and transfers illustrate that these variables increase the general cost of a BART trip. Conversely, the model predicts that high service frequencies and competitive travel times (i.e., a higher ratio between auto travel time and BART travel time) positively influence ridership. Direct competition with the MUNI light rail is predicted to reduce ridership.[22] The inverse transformation of OD distance (1/distance) has a very significant and negative correlation with ridership, demonstrating a sharp decrease in riders when an OD pair lies in close enough proximity that walking can substitute for a potential BART trip. The model predicts that connecting buses at either the origin or destination will significantly increase ridership, which shows that bus feeders can be an effective tool along with parking in extending the reach of a rail system. The model also predicts that the large catchment area of a terminal station can positively affect ridership. This holds true when the terminal station serves as the origin or destination. Having a sports stadium at the destination also correlates with increased ridership.

A 1 percent increase in the housing index (*housing_o*) results in a 0.43 percent increase in ridership. However, because the housing variable is used in some of the interaction terms (as previously described), this coefficient value proves meaningful only when *ln*(*bart_tt*) and *ln*(*parking_o*) are both equal to 0. The marginal coefficient (i.e., the coefficient value that accounts for the moderating effects of the interaction terms) of housing for a particular OD pair will depend on BART travel time and the amount of parking at the origin station. Among the various BART OD pairs in this analysis, the estimated marginal coefficient for the housing index ranges from –.01 to .71 with a median value of .21. The Pleasant Hill to Dublin/Pleasanton OD pair (see Figure 1) has the lowest housing coefficient. This is a long suburb-to-suburb trip that takes more than sixty minutes, and the origin station (Pleasant Hill) has more than three thousand park-and-ride spaces. In this situation, nearby housing is estimated to have no real influence on ridership. The highest housing coefficients (~.7) apply to a handful of OD pairs in downtown San Francisco and Oakland where the origin stations have no parking and BART travel time is only one minute.

As with the housing variable, the coefficient for the destination employment variable (*jobs_d*) of .23 applies only when *ln*(*bart_tt*) and *ln*(*parking_o*) equal 0. The actual range of this marginal coefficient falls between .12 and .46 with a median value of .35. The coefficients for destination jobs follow the opposite pattern of those for origin housing: closely spaced OD pairs with little or no parking at the origin (such as those that begin and end in downtown San Francisco or Oakland) have low marginal coefficients, while long-distance OD pairs with large numbers of parking spaces at the origin station (such as Pleasant Hill to Dublin Pleasanton) have large marginal coefficients.

The estimated origin parking, *ln*(*parking_o*), coefficient of .17 is only meaningful when *ln*(*housing_o*), *ln*(*auto_tt*/*bart_tt*), and *ln*(*jobs_d*) equal 0. Among the 1,064 BART OD pairs that have a parking facility at the origin station, the marginal coefficient for parking ranges from –.22 to .64 with a median value of .14. The negative values at the bottom of the range indicate that, in certain situations, the presence of parking at an origin station has a negative influence on ridership. This likely stems from the fact that a large parking facility can have a detrimental effect on the pedestrian environment. This detrimental effect appears most dominant when there is a large amount of housing near the origin station (the parking facility may impede pedestrian access for the residents of this housing), when there are few jobs at the destination station (providing little attraction for park-and-ride commuters), and/or when BART is slow relative to driving (making it likely that someone with access to a car would simply drive to his or her destination). The lowest marginal coefficient for origin parking (–.22) is estimated for the Ashby to Pittsburg/Bay Point OD pair. The origin station (Ashby) has a decent amount of housing (more than four thousand units within a half mile), and the destination station (Pittsburg/Bay Point) has very few jobs (less than one hundred within a half mile). Because this OD pair flows opposite the prevailing traffic patterns, driving from station to station only takes three-quarters of the time it would take using BART. Conversely, the marginal coefficient for origin parking is highest (.64) for the Orinda to Montgomery OD pair. The origin station (Orinda) has relatively little housing (less than three hundred units within a half mile), the destination station (Montgomery) has thousands of nearby jobs (nearly one hundred thousand within a half mile), and driving from station to station during the peak period would take three times longer than using BART because the driving route encounters two major traffic bottlenecks (the Caldecott Tunnel and the Bay Bridge). Parking at the destination (*parking_d*) was also included in the model to reflect the fact that having a large parking facility at the destination makes it less attractive to BART riders who walk from the station to their final destinations. It has coefficient of –.17, meaning that a 1 percent increase in parking at the destination will result in a 0.17 percent decrease in ridership.

Net Effects of Parking Replacement

The main objective of this research is to determine how the removal of parking in favor of development would influence ridership. As such, a high or low marginal coefficient for a particular variable means little in and of itself. What does matter is whether housing or employment has a large marginal coefficient *relative* to the corresponding marginal coefficient for parking. The size of the marginal coefficients for these variables depends heavily on the unique set of attributes associated with each OD pair. Thus, the relative influence of parking as compared to housing/employment on ridership will also vary for each OD pair.

A station-level change (e.g., adding housing in place of parking) will influence ridership for the thirty-eight OD pairs originating at a given station and the thirty-eight OD pairs terminating at the same station. The ridership implications of such a change are complicated because, as indicated by the significant interaction terms, the change in ridership will not be uniform for each of the affected OD pairs. Consequently, the best way to assess the impact of parking replacement is through the net change in system-level ridership. A successful parking replacement program would not necessarily increase or even maintain ridership for every affected OD pair. The following discussion will focus on finding a parking replacement scenario that has a neutral effect on ridership. In other words, any lost ridership on a given OD pair must be fully replaced by gains on another OD pair.[23]

Predicted Effect of Parking Removal

The first step in defining a parking replacement scenario is simply examining what would happen if the parking facilities were removed (without adding any new development). Parking removal will have two countervailing effects. The first and more obvious would be to reduce the number of trips originating from the affected station. A few of the OD pairs may actually see an increase (as previously discussed), but the net effect is always predicted to be negative. The other less obvious influence of removing parking is to make a station more attractive as a destination. The significantly negative coefficient for the *parking_d* variable provides empirical backing to this assertion. The number of trips terminating at a station is predicted to increase when parking is removed. The magnitude of this positive influence is relatively minor, but nonetheless, it deserves consideration when determining the net influence of parking removal.

Among the thirty-nine BART stations, twenty-eight have park-and-ride facilities. For each of these twenty-eight stations, the model coefficients are used to predict the change in passenger counts resulting from parking removal.[24] Table 4 presents these predicted changes. Because of lack of space, the confidence intervals for these ridership changes are not displayed, but the reader should keep in mind that presented values are only approximations.

The estimated loss in trips originating at a particular station ranges anywhere from five hundred to three thousand passengers. In percentage terms, ridership losses range from 26 to 82 percent. As one might expect, the suburban stations with little housing nearby lose the largest share of their ridership. The more urban locations (e.g., Oakland and Berkeley) fare better without parking because they have much greater supplies of nearby housing. As previously described, the influence of this housing on BART usage will increase with the removal of parking (i.e., the marginal coefficient for the housing index increases with the removal of parking).

The estimated gain in trips terminating at a station ranges from one hundred to fourteen hundred or from 20 to 81 percent. The predicted size of this gain largely relates to the size of the parking facility that is removed (the larger the facility, the greater the gains from its removal) and the number of trips that were previously coming to the station. A few BART stations have a park-and-ride lot surrounded by an office center (e.g., Walnut Creek, Fremont, and Pleasant Hill), and these stations are predicted to gain the largest number of exits with the removal of parking.

The combined effect of lost boardings and gained exists represent the system-level impact on ridership. For all of the BART park-and-ride stations, the lost boardings dominate the gained exists. Thus, parking removal is always predicted to result in a net loss in ridership. This loss is predicted to range from 150 to 2,500 riders or from 4 to 54 percent. The net loss in ridership resulting from parking removal serves as the target for the amount of riders any new development will need to generate.

Development Threshold for Parking Replacement

Based on the predicted ridership losses, the amount of development needed to maintain ridership is estimated. For the purposes of this analysis, the replacement levels of housing and jobs will be calculated separately. This allows for an assessment of what kind of development might work best at a particular station. However, this is a methodological simplification that should not be seen as a prescription to avoid mixing of land uses. Such mixing is a key aspect of TOD because it facilitates more pedestrian trips within the development. It is less clear how the mixture of housing and commercial uses at any particular station will influence BART usage.[25]

Replacing parking with housing will more directly replace the trips that previously originated at the affected station, although the destination pattern for these trips will likely change. Since the marginal housing coefficient decreases with OD travel time in a way that parking does not, a net neutral impact on ridership likely means that fewer trips will be made to more distant destinations, and these losses will be offset with increased trips to more proximate destinations.

The replacement of parking with employment will lead to an entirely different pattern of ridership. Trips that previously originated at the affected station will not come back. They will be replaced by trips originating at other stations and terminating at the affected station. Ironically, these new trips may originate at park-and-ride stations. As such, replacement of parking with employment will not necessarily lead to any reduction in the percentage of BART passengers who reach the station by driving. Furthermore, the effectiveness of replacing parking with employment would decrease if such a strategy were pursued at multiple stations. An OD pair where both stations serve as employment centers will have limited ridership. If all parking were replaced with employment, there would too many OD pairs that lack trip generators at the origin, and system ridership would likely decrease. Thus, replacing parking with nonresidential development would only be a good strategy on a targeted basis.

For all of the BART park-and-ride stations, Table 5 presents the estimated amount of housing units or employment needed to replace a parking facility while maintaining ridership. The density per acre and the FAR (floor area ratio) calculations rely on the assumption that each parking space that is removed will open up 350 square feet (0.008 acres) of land for development. This is a relatively standard amount for surface parking (Willson and Menotti 2007). However, some stations have a mixture of structured and surface parking (Colma, Daly City, El Cerrito del Norte, Walnut Creek, Pleasant Hill, Concord, Hayward, and Dublin/Pleasanton). For these stations, the development thresholds only apply for the surface parking. In the unlikely event that one of these parking structures were to be torn down in favor of development, the required density to maintain ridership may be up to five times higher (depending on the height and layout of the parking structure). The FAR calculations also rely on assumptions about the average floor space per housing unit or job. This is assumed to be 1,000 square feet for housing and 500 square feet for jobs, which are appropriate estimates for the kind of high-intensity development one might expect in a TOD. While the assumptions used to make the calculations in Table 5 have been carefully considered, there is obviously some real-world variation in the amount of floor area used by a housing unit or job, and different assumptions could produce very different results.

The density thresholds for housing are strikingly high. The majority of the park-ride stations are predicted to need in

Table 4. Predicted Ridership Changes Resulting from Parking Removal

		Trips originating at station				Trips terminating at station				
Station	Parking spaces	Before removal	After removal	Change	Percentage change	Before removal	After removal	Change	Percentage change	Net change
El Cerrtio del Norte	2,155	5,604	2,669	–2,935	–52	731	1,232	501	69	–2,434
Pittsburg/Bay Point	1,873	3,616	1,105	–2,512	–69	488	804	316	65	–2,196
Pleasant Hill	3,343	4,090	1,548	–2,542	–62	664	1,202	538	81	–2,004
Dublin/Pleasanton	2,751	3,367	604	–2,763	–82	1,418	2,486	1,068	75	–1,695
Colma	2,392	4,044	1,917	–2,127	–53	818	1,401	584	71	–1,543
Concord	2,408	3,469	1,417	–2,052	–59	980	1,682	702	72	–1,351
West Oakland	390	2,872	1,434	–1,439	–50	768	1,002	234	31	–1,204
Fruitvale	773	4,604	2,817	–1,787	–39	1,333	1,916	583	44	–1,204
Bayfair	1,543	3,223	1,600	–1,623	–50	914	1,461	547	60	–1,077
LaFaytte	1,484	1,993	595	–1,397	–70	576	915	339	59	–1,058
Orinda	1,287	1,602	348	–1,254	–78	469	729	260	55	–995
Walnut Creek	1,804	3,019	1,025	–1,994	–66	1,623	2,660	1,037	64	–957
Rockridge	862	2,560	1,433	–1,128	–44	541	790	250	46	–878
El Cerrito Plaza	706	2,969	1,873	–1,097	–37	545	773	228	42	–869
North Concord	1,889	1,400	400	–1,000	–71	237	391	154	65	–845
Castro Valley	973	1,561	805	–756	–48	201	300	98	49	–657
San Leandro	1,173	3,038	1,651	–1,388	–46	1,431	2,191	760	53	–627
Union City	1,096	2,254	1,036	–1,218	–54	1,178	1,785	607	52	–611
South Hayward	1,246	2,044	997	–1,048	–51	875	1,353	478	55	–570
Daly City	1,921	3,887	2,231	–1,656	–43	1,727	2,859	1,131	65	–524
North Berkeley	742	2,251	1,511	–740	–33	512	731	220	43	–520
MacArthur	579	3,352	2,205	–1,148	–34	1,838	2,534	696	38	–452
Coliseum	1,017	3,310	1,555	–1,754	–53	2,621	3,927	1,306	50	–448
Ashby	594	2,376	1,694	–682	–29	854	1,182	328	38	–355
Richmond	563	2,507	1,792	–715	–29	983	1,350	367	37	–348
Fremont	1,932	3,199	1,490	–1,709	–53	2,086	3,455	1,369	66	–340
Hayward	1,425	2,468	1,344	–1,125	–46	1,613	2,546	933	58	–192
Lake Merrit	195	2,130	1,577	–553	–26	1,925	2,307	383	20	–170

Table 5. Predicted Parking Replacement Thresholds

		New housing units adjacent to station				New jobs adjacent to station			
Station	Ridership target	Total	Units per parking space	Units per acre	FAR[a]	Total	Units per parking space	Units per acre	FAR[a]
El Cerrtio del Norte	2,434	6,000	2.8	348	8.0	22,900	10.6	1,328	15.2
Pittsburg/Bay Point	2,196	6,850	3.7	457	10.5	1,100	0.6	73	0.8
Pleasant Hill	2,004	12,200	3.6	456	10.5	17,500	5.2	654	7.5
Dublin/Pleasanton	1,695	5,500	2.0	250	5.7	6,200	2.3	282	3.2
Colma	1,543	3,650	1.5	191	4.4	4,800	2.0	251	2.9
Concord	1,351	5,900	2.5	306	7.0	9,800	4.1	509	5.8
West Oakland	1,204	3,200	8.2	1,026	23.5	13,250	34.0	4,247	48.7
Fruitvale	1,204	2,350	3.0	380	8.7	4,300	5.6	695	8.0
Bayfair	1,077	3,300	2.1	267	6.1	2,600	1.7	211	2.4
LaFaytte	1,058	5,500	3.7	463	10.6	4,800	3.2	404	4.6
Orinda	995	4,400	3.4	427	9.8	2,200	1.7	214	2.5
Walnut Creek	957	3,500	1.9	243	5.6	4,900	2.7	340	3.9
Rockridge	878	4,500	5.2	653	15.0	8,100	9.4	1,175	13.5
El Cerrito Plaza	869	3,250	4.6	575	13.2	6,550	9.3	1,160	13.3
North Concord	845	6,600	3.5	437	10.0	1,600	0.8	106	1.2
Castro Valley	657	4,400	4.5	565	13.0	21,400	22.0	2,749	31.6
San Leandro	627	2,050	1.7	218	5.0	1,600	1.4	171	2.0
Union City	611	2,000	1.8	228	5.2	400	0.4	46	0.5
South Hayward	570	2,300	1.8	231	5.3	300	0.2	30	0.3
Daly City	524	1,400	0.7	91	2.1	250	0.1	16	0.2
North Berkeley	520	2,800	3.8	472	10.8	3,800	5.1	640	7.3
MacArthur	452	1,450	2.5	313	7.2	900	1.6	194	2.2
Coliseum	448	650	0.6	80	1.8	300	0.3	37	0.4
Ashby	355	1,900	3.2	400	9.2	1,500	2.5	316	3.6
Richmond	348	1,250	2.2	278	6.4	1,400	2.5	311	3.6
Fremont	340	1,200	0.6	78	1.8	350	0.2	23	0.3
Hayward	192	600	0.4	53	1.2	250	0.2	22	0.3
Lake Merrit	170	500	2.6	321	7.4	950	4.9	609	7.0

[a] FAR (floor area ratio) is the floor area of a structure divided by the land area of the parcel on which the structure is built.

excess of three hundred units per acre. This goes well above what is typically found anywhere except the most urban environments. Only four of the stations have a density threshold below one hundred units per acre (Daly City, Coliseum, Hayward, and Fremont), and two of these stations already have structured parking (Daly City and Hayward) that will deter parking replacement.

The employment replacement thresholds are generally more realistic. The estimated FAR threshold for employment is lower than the FAR for housing at nearly all of the stations. There are seven stations that have thresholds less than one hundred jobs per acre (FAR < 1). This might be reasonable even at the more suburban stations. Nonetheless, most of the stations would still require three hundred jobs per acre (FAR > 3). This well exceeds what is traditionally found in Bay Area suburbs (Cervero 1989).

The relative effectiveness of employment as compared to housing is an interesting finding that merits further discussion. This may stem from the fact that being adjacent to the station is of greater importance at the nonhome end of a transit trip. BART (1999) passenger surveys indicate that the average walking distance from home to the station is longer than the average walking distance from the station to the final destination. This is further evidenced by the fact that when testing weights for the housing and job indices, the optimal (in terms of model fit) distance decay function is steeper for the job index. Consequently, when development options are limited to the immediate station area (as they would be with parking replacement), employment may be expected to have a stronger influence on ridership.

Another reason may relate to the moderating influence of BART travel time. The influence of housing decreases with travel time while it increases for employment (i.e., increased travel time causes the marginal coefficient for housing to decrease and the marginal coefficient for employment to increase). This indicates that adding employment has a much wider reach and will draw new riders from a variety of stations across the system.

Policy Implications of Station Development

Expanding the Geographic Scale of Station Development

The previous discussion has focused explicitly on development in the areas currently occupied by park-and-ride lots. However, development outside of the immediate station can also influence ridership. This holds particularly true for housing. Depending on the connectivity of the street network, a BART station might have somewhere between twenty and one hundred acres of land within a quarter-mile walk, and the supply of land will exponentially increases moving outward from the station. Making use of land beyond the parking area would allow for more reasonable development densities while still maintaining passenger demand.

Such a strategy has several difficulties. First, it requires that a sufficient share of the land within walking distance is either undeveloped or has potential for redevelopment at higher densities. Second, unlike station parking, the rest of the land within walking distance generally falls outside of the control of the transit agency. Local governments and private landholders must be relied upon to facilitate TOD that extends beyond the parking lot. However, unlike a transit agency, these entities may have little stake or interest in building TOD (Levine 2005). This does not make such development impossible,[26] but increasing the number of stakeholders will certainly make the process more complicated (TCRP 2004).

A final consideration on this topic is whether transit agencies wish to maintain or maximize ridership. If it is the latter, the best strategy might be to keep the park-and-ride facility while trying to facilitate more development in the surrounding area. This would allow for the attraction of both park-and-ride and walk-and-ride passengers. However, the negative interaction between housing and parking demonstrated in this analysis (i.e., the marginal coefficient for housing decreases with the size of a parking facility) illustrates that trying to combine housing and parking together may not provide an optimal strategy.

Parking Replacement Policy

Many rail operators (including BART) have a 1:1 parking replacement policy (TCRP 2004). This means that they will accept proposals for development on their surface lots but that all of the removed spaces must be replaced with structured parking. Even though the provision of parking seems a realistic way to maximize BART riders at most stations, this does not justify a 1:1 parking replacement policy. While new development may not offset all of the lost ridership, it will certainly replace some of it. This is best illustrated with an example. A hypothetical station may require a housing development with 150 units per acre to replace a park-and-ride lot without losing riders. While a developer would not likely build at such a density, one might build at 50 units per acre. This development would generate enough riders to offset a third of the parking spaces. Consequently, only two out of three parking spaces need replacement to maintain ridership. While the necessary parking structure would still create an expensive barrier to development, the cost savings of building a parking structure with seven hundred spaces instead of one thousand spaces might push a project into financial viability. A more sensible approach than 1:1 replacement would be an adjustable scale determined by the parking replacement threshold specific to each park-and-ride facility and the density of the proposed development.[27] Such a scale could be further adjusted downward if the developer and transit agency could work out a deal to share parking.

Conclusions

The provision of park-and-ride facilities at a rail station leaves something to be desired from a sustainability perspective. However, such facilities do have the benefit of widely expanding the number of people with access to the system, and this is generally thought to translate to greater ridership. My analysis represents an effort to see what it would take to maintain these ridership benefits without parking. The results indicate that the answer to this question is highly variable. The model has several significant interaction terms, which indicate that the relative influence of parking, housing, and employment is highly dependent on the specific attributes of an OD pair. One important implication for transit planning is that housing is predicted to have stronger influence on ridership when an OD pair is closer together. This means that extensive systems with widely spaced stations (such as BART) may be less amenable to TOD.

For the most part, the level of residential density needed to have a net neutral impact on ridership appears to go beyond realistic levels (unless the citizenry and their government representatives are looking to make a drastic change to the status quo of development patterns). There are only a handful of stations that could maintain ridership with less than one hundred units per acre. The commonality among these stations is that a significant amount of development surrounds the parking facility, and the removal of parking not only frees up land for new development but makes the station more attractive for those who already live, work, or otherwise conduct activities nearby. This suggests that if development is encouraged around the parking facility, the replacement of parking with TOD may eventually become more feasible. There are some additional stations throughout the system where replacing parking with a moderately dense employment center is predicted to generate a net increase in ridership, but this will not necessarily reduce reliance on station parking. The successful replacement of parking with employment relies on the existence of other nearby park-and-ride stations to feed the new job center. In sum, the key finding from this research is that, for most BART stations, replacing parking with development does not represent a practical strategy with regard to ridership.

BART's apparent dependence on parking for ridership has important implications for the planning and construction of TOD. Given that parking replacement may not be realistic or desirable (from a ridership perspective), trying to better integrate parking and development provides a pragmatic approach to expanding the inventory of TOD. Urban designers and traffic engineers might be enlisted to help design parking facilities that do not significantly detract from the pedestrian environment.

Despite any potential for integration of parking and development, TOD and park-and-ride facilities are fundamentally in competition for the same land. The ridership advantages of parking observed in this research indicate that replacing parking with TOD will require a more robust justification that goes beyond ridership. Thus, a natural extension of this work would be to compare TOD versus parking facilities in terms of outcomes such as vehicle miles traveled, emissions, energy consumption, and access for disadvantaged populations. The opportunity cost of using valuable land for parking might also be more carefully considered (TCRP 2004). In a broader evaluation, TOD may be shown to have benefits that outweigh the ridership advantages of parking provision. To the degree that TOD does have such benefits, a better understanding is required of the motivations and incentives of transit agencies and how they might be compelled to consider broader sustainability goals.

Appendix

Aggregate versus Disaggregate Models

This research makes use of aggregate rider counts for each origin-destination (OD) pair in the Bay Area Rapid Transit System (BART) rail network. Such data are used because they provide a straightforward approach to testing the research question at hand. Nonetheless, there are downsides to aggregate data that deserve further discussion. The passenger counts used in this analysis represent an amalgamation of many individual travel choices. These choices are based on individual characteristics (e.g., socioeconomic status, attitudes, and lifestyle preferences) that influence demand for travel and the perceived cost of various travel modes (Recker, McNally, and Root 1986). Modeling aggregate outcomes obscures the individual-level influences, and consequently, such an approach lacks a strong theoretical tie to travel behavior (Boarnet and Crane 2001; McFadden 1974).

When a research question is about individual travel behavior (e.g., What individual characteristics influence the likelihood a making a BART trip?), the most appropriate unit of analysis is obviously the individual (or household) making the travel choices. However, such a disaggregate analysis may prove less suitable when it comes to measuring aggregate usage of transport facilities (as is the case with this research). This would require that the disaggregate model be "applied" to each individual in the study area. In other words, the coefficients estimated in the disaggregate model must subsequently be used to predict the travel behavior of every individual. These individual predictions can then be summarized to measure usage of a facility. Given that a database containing a full enumeration of the population is rarely available for model application, a representative sample must be used in its place. As such, the degree to which a sample truly represents the demographic and spatial distribution of the population will determine whether a model application can produce an accurate assessment of aggregate usage of a facility.

The lack of an appropriate sample for model application was a major reason why this research does not use a disaggregate

(continued)

Appendix (continued)

approach. The 2000 Bay Area Travel Survey (BATS) likely provides the best available sample[a] for this study area. It has a seemingly large sample of thirty thousand people that provides a more than adequate database for model *estimation*. In fact, many researchers have used this very data to conduct disaggregate analysis of travel data (e.g., McDonald 2007; Cervero and Duncan 2006). However, unlike model *estimation*, the accuracy of a model *application* may have more to do with the percentage of the population covered by a sample rather than the raw sample size. The BATS represents only a half percent sample of the region's population, meaning that each BATS respondent represents an average of two hundred people. The average number of passengers on a BART OD pair is only eighty-two. Consequently, the total ridership on most OD pairs is represented by only a fraction of a person from the BATS sample. This makes it highly unlikely that the model application can accurately predict ridership at an OD scale.

The model application takes the accurate prediction of an individual's BART usage as a given. However, in practice, this can also present great difficulty. As previously described, disaggregate analysis of transit ridership often focuses on mode choice models that predict the likelihood a making a specific trip (i.e., a trip with a specific origin, destination, and time of day) by a given mode. However, simply predicting the probability of using BART for a given trip is not sufficient for this analysis. To estimate aggregate BART passengers for each OD pair and compare the influence of parking and development on ridership, it would be necessary to predict the following elements of individual travel behavior:

1. the number of BART trips made during a given time period,
2. the boarding station for each BART trip,
3. the mode used to travel from the place of origin to the boarding station,
4. the exit station for each BART trip, and
5. the mode used to travel from the exit station to the final destination.

A single model could not simultaneously predict each of these choices. As such, the disaggregate analysis would require a sequence of models. For example, using the traditional four-step travel demand model as a guide, one might use the following sequence:

1. Predict the total number of trips (by any mode) for a given individual.
2. Predict the destination of these trips (e.g., estimating the probability of the destination being located in a particular zone).
3. Predict the mode used for each of these trips (e.g., estimating probability of using BART along with the probability of using a given mode of access and egress).
4. Predict the link(s) of the network used to make the trips (e.g., estimating which BART OD pair is used to get from one's home to a predicted destination zone).

Aside from the large amount of time and data that this process would require, the general idea of using a sequence of models has flaws. One can question how well the order of a model sequence mimics the way that people make travel decisions. To this end, some modelers have introduced feedback loops that account for the fluidity and simultaneity of the various choices that determine travel outcomes. Error propagation represents another, less correctable, problem with a model sequence (Zhao and Kockelman 2002). The predictions from one model are used as inputs to the next and this means that the uncertainty (i.e., the error term) associated with the early stage predictions becomes amplified as it moves through the sequence. The error term in the final stage of the model can become large enough that the predictions are no longer useful.[b] From a nontechnical perspective, a sequence of models can create a "black box" feel that can confound the understanding of those not intimately involved in the modeling process. Ironically, the strategies used to address technical problems (e.g., the previously discussed feedback loops) can exacerbate the lack of transparency.

Given that that this research does not address a question that fundamentally requires a disaggregate analysis, the above described difficulties in using a disaggregate approach led to the use of a single model that predicts aggregate rider counts. The outcome of interest (i.e., passenger counts) serves as the dependent variable, and the inputs of interest (i.e., station area development and parking) serve as the independent variables. While a strong theoretical connection to travel behavior is sacrificed, the chosen approach provides a direct, transparent, and accurate way the measure the influence of station area attributes on ridership (Cervero 2006).

Home-Origin Passengers

The mechanically collected passenger counts were combined with BART (1999) survey data to produce an estimate of "home-origin" passengers for each BART OD pair. For each OD pair an original estimate was set for the number of home-origin passengers based on the survey data for that OD pair. The number of survey respondents for most OD pairs was too small to rely on this alone. However, aggregated to the station level, the estimated percentages for home-origin passengers are much more reliable. As such, an iterative proportional fitting

(continued)

Appendix (continued)

procedure was implemented (Simpson and Tranmer 2005). After the initial OD estimate of home-origin passengers, the sum of these home-origin passengers was calculated for each origin station. Each OD pair was then adjusted so that the percentage of home-origin passengers originating at a given station was equal to the percentage defined by the BART survey. The total home origin passengers terminating at each station was then calculated and each OD pair adjusted so that the percentage of home-origin passengers terminating at particular station matched the percentage from the BART survey. This process was then repeated until convergence was achieved.

This process is not perfect and will introduce some error into the data. Testing was done to ensure that this error was not significantly hindering the accuracy of the model predictions. This testing involved the estimation of three models with different dependent variables:

1. unadjusted total passenger counts,
2. estimated home-origin passenger counts (as produced by the iterative proportional fitting [IPF] procedure), and
3. estimated non-home-origin counts (unadjusted counts – home-origin counts).

The real objective is to compare the accuracy of (1) to (2), but it is difficult to compare models that do not have the same dependent variable. To make a relevant comparison, the predicted value of (1) was compared to the sum of the predicted values for (2) and (3). It was found that the sum of the prediction for (2) and (3) explains more of the variation in actual passenger counts than does the predicted value of (1). This indicates that, despite the error that is introduced as a result of the IPF procedure, the segmentation of the model has efficiencies that offset this error.

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[a] Other population samples have serious limitations with respect to this analysis. The Public Use Micro-Sample (PUMS) database provides a large (5 percent) population sample of every U.S. region but lacks geographic specificity. Proximity to stations is critical to BART ridership, making the PUMS unsuited to this task. The U.S. Census does provide demographic information with specific geographic locations, but these data are aggregated to zones. The aggregation limits the use of these data as a population sample. The census does provide tabulations that count the number of households/people in each zone that fall into specific demographic categories. However, these fall well short of the detailed cross-tabulations that would be needed for proper application of a complex behavioral model.

[b] The true magnitude of error propagation in travel modeling is largely unknown because, in practice, tracking the error term across a model sequence rarely, if ever, occurs.

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Notes

1. Of the roughly 350 light rail stations that have been built in the United States since 2000, about 40 percent have a park-and-ride facility.
2. The passengers lost by removing parking might also be replaced by increasing the number of bus connectors to the station. However, this is not a relevant scenario because bus service and parking are not direct substitutes. Increasing bus frequency would require little, if any, additional land area. Most Bay Area Rapid Transit System (BART) stations already have bus bays, and expansion of these bays to accommodate more buses can require as little as six hundred square feet, which is the equivalent of two or three parking spaces. In other words, increasing bus access to BART stations would not require any significant removal of parking.
3. One job is generally equivalent to three hundred to one thousand square feet of commercial space.
4. It should be noted that methodological difficulties (e.g., controlling for the effects of self selection) make it difficult to determine how much transit-oriented development (TOD) may actually influence travel behavior (Cao, Mokhtarian, and Handy 2009; Crane 2000).
5. Bus connections can also extend a station's catchment area, but the geographic scope is more limited because it only reaches those who live along the bus routes.
6. While public subsidies relieve the pressure on public transit operators to chase fare revenue, such revenue does represent a significant portion of the operating budget. Fare revenue has the additional advantage of not being subject to the political uncertainty of public funding. Thus, transit operators still have a significant incentive maximize fare revenue.
7. If TOD housing is not affordable, it will do little to help those who cannot afford private transport.
8. "Cold start" and "hot soak" emissions will occur independent of the trip length. "Cold start" refers to the period immediately after vehicle ignition when the catalytic converter is still cold and does not properly filter pollutants. "Hot soak" refers to the time after the vehicle is turned off but evaporative emissions continue because the engine is still hot. Furthermore, if a parking lot is not shaded, these evaporative emissions can occur for the entire period the vehicle is parked (Scott, Simpson, and McPherson 1999).
9. Rail systems have attributes that make them conducive to development impacts (as compared to bus systems): high-quality service, good image, and permanent infrastructure (Hess and Bitterman 2008; Currie 2006; Ben-Akiva and Morikawa

2002). Whether the unfettered development impacts of rail truly justify the large capital costs of rail investment is open to debate. However, the absence of such impacts certainly buttresses the arguments of those who consider rail a wasteful investment (Winston and Maheshri 2007; Rubin, Moore, and Lee 1999; Pickrell 1992).

10. BART has since expanded to forty-three stations.
11. If a standard ordinary least squares model is used with nested data, it can lead to biased coefficient and standard errors, especially for station-specific variables (e.g., parking, housing, and employment) that will have the same value repeated across multiple observations. This is due to the fact that nested data violates the assumption that each observation is independent of other observations.
12. This type of model can be estimated in STATA using the "XTMIXED" command. The term "cross-classified" indicates that the two upper level categories (origin station and destination station) do not nest with each other the way they nest with the lower-level category (origin-destination [OD] pairs).
13. Most of the interactions are cross-level interactions and have 1,482 unique values. The interaction between two origin station characteristics only has 39 unique values and is treated as such when calculating the standard error of its coefficient.
14. The skewness of the untransformed variable is 3.99, but when logarithmically transformed it shrinks to 0.16 (0 is a completely symmetrical distribution).
15. A count model can also handle such problems. Count models are designed to handle skewed data with only positive integers. A negative binomial count model was tested and produced results that were very similar to the semi-log model both in terms of coefficient size and statistical significance. Given that a simple transformation of the dependent variable is more generally understood than a count model, the semi-log model was chosen for this analysis.
16. The log-log transformation allows the model coefficients to be interpreted as an elasticity. In other words, the model coefficients represent the percentage increase in riders predicted to occur with a 1 percent increase in an independent variable.
17. A simpler approach might be to estimate a model for A.M. peak period when most trips originate from a rider's home. However, BART OD passenger data broken down by time of day could not be obtained.
18. If the dependent variable was specified as total daily passenger counts, those who are leaving home would be mixed in with those returning home (and also a few who are neither returning nor leaving from home). The set of variables used for both the origin and destination station would need to account for home-end trip generators *and* nonhome activities. In fact, the variables specified for the origin and destination would mirror each other, as would their corresponding coefficients. In addition to making for a confusing specification, the increased number of variables increases the potential for multicollinearity and makes it more difficult to estimate statistically significant coefficients.
19. The terminal station variable serves to capture the amount of people that might consider using a station rather than the ease with which they can arrive at the station. This holds true for both origin and destination stations.
20. In addition to measuring the number of people who work nearby, station area employment also acts a general proxy for commercial activities (e.g., retail, service and entertainment opportunities) that might serve as nonwork trip destinations.
21. Other interactions that were tested but proved statistically insignificant include the following:

    origin housing × destination employment
    origin housing × auto/BART travel time ratio
    origin parking × BART travel time
    destination employment × auto/BART travel time ratio.

22. MUNI runs a parallel-grade separated service in downtown San Francisco.
23. It should be noted that a neutral impact on ridership does not necessarily translate to a neutral impact on fare revenue. As BART has a distance-based fare system, any scenario that replaces long trips with short trips will reduce revenue. Parking replacement scenarios that were neutral with regard to revenue were tested and were only slightly different than the ridership neutral scenarios.
24. The predicted scenarios are based on what would happen if parking were replaced at only one station.
25. Interactions between housing and employment (retail employment in particular) at the origin station were tested, but these interactions were not significant. Because of the small sample size, it is difficult to know whether this occurs because there is really no impact on ridership or whether there are simply not enough degree of freedom to statistically measure the impact.
26. There are many examples of transit agencies, local governments, and private developers working together to build TOD. For some specific examples, see the various case studies in TCRP Report 102 (Transit Cooperative Research Program [TCRP] 2004).
27. A parking replacement ratio could be determined by this simple formula:

    1 – (proposed development density/station specific parking replacement density).

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