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Alternative Approaches to Modeling the Travel-Demand Impacts of Smart Growth

Robert Cervero

Four-step travel demand forecasting models were never meant to estimate the travel impacts of neighborhood-level smart growth initiatives like transit villages, but rather to guide regional highway and transit investments. While progress has been made in enhancing large-scale models, some analysts have turned to post-processing and direct models to reduce modeling time and cost, and to better capture the travel impacts of neighborhood-scale land use strategies. This paper presents examples of *direct* or *off-line* modeling of rail and transit-oriented land use proposals for greater Charlotte, the San Francisco Bay Area exurbs, and south St. Louis County. These alternative approaches provided a useful platform for scenario testing, and their results revealed that concentrating development near rail stations produced an appreciable ridership bonus. These alternative models are appropriate as sketch-planning supplements to, not substitutes for, traditional four-step models.

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No field in planning makes greater use of statistical models for looking into the future than transportation. All metropolitan planning organizations (MPOs) maintain and routinely update large-scale travel demand models to guide capital investments. As Pas (1995) noted, travel forecasting is “oriented almost exclusively toward analysis of long-term, capital-intensive expansion of the transportation system, primarily in the form of highways” (p. 55). In recent times, the smart growth movement has sparked a new round of interest in travel forecasting, less to guide investments than to gauge potential reductions in demand for travel. Transit-oriented development (TOD), new urbanism, and new towns intown will prompt Americans to drive less, and walk, bike, and ride transit more, proponents contend. But can contemporary travel forecasting models reflect this?

Predictably, transportation analysts have generally turned to what is available (notably four-step travel models¹) to estimate the travel impacts of smart growth. While the four-step process enjoys widespread support from decades of use, it was never meant to estimate the travel impacts of neighborhood-scale projects or development near transit stops. Four-step models’ primary units of analysis, Traffic Analysis Zones (TAZs), range in size from block groups to census tracts, allowing study of land-use futures at meso and macro scales: corridors, subregions, metropolitan areas, and states. Their resolution tends to be too gross to pick up fine-grained design and land-use-mix features of neighborhood-scale initiatives like new urbanism and TOD. Even much-touted activity-based microsimulation models like TRANSIMS are regional in scope and have yet to be operationalized for studying fine-grained transportation/land use relationships.

This article presents alternatives to traditional modeling of neighborhood-scale projects, discussing shortcomings of the four-step approach and reviewing two alternative approaches: post-processing and direct, or off-line, modeling. I then present examples of these alternative approaches. Besides demonstrating off-line modeling as a platform for studying neighborhood-scale smart-growth strategies, my analyses also gauge the influence of built environments on transit patronage in three contrasting settings, highlighting TOD’s contribution to increased ridership. The article closes with suggestions on how alternative modeling approaches might gain institutional and analytical legitimacy.

Shortcomings of the Four-Step Approach

All planning models have shortcomings. This section reviews limitations of the four-step travel models, particularly in how they capture the influences of land use and urban design on travel demand, as well as noting some recent enhancements.

Trip Generation

MPOs typically use regression equations or cross-tabulated trip rates to estimate numbers of trips per household as a function of socioeconomic variables like household size, income, and auto ownership. They also use regression equations to estimate the number of trips that will be attracted to a TAZ, usually as a function of the number of jobs located there, the number of residents, and other gross activity measures. Rarely are variables like neighborhood density, employment density, or ease of walking access used as predictors. Missing altogether are measures of land use mix. The commingling of offices, shops, eateries, and condos within a master-planned project, research shows, can “de-generate” (reduce) vehicle trips through “internal capture” by as much as 55% (Ewing & Cervero, 2001; Institute of Transportation Engineers, 2003).

Trip de-generation is sometimes also a product of self-selection; those with a predisposition to live in a walkable neighborhood deliberately move to places with mixed uses and traditional grid street patterns. A recent study in the San Francisco Bay Area suggests that upwards of 40% of the ridership bonus associated with TOD is a product of residential self-selection (Cervero & Duncan, 2003). MPOs' land use data inputs to trip generation analyses are not sensitive to the dynamics of residential self-selection; thus the tendency of people who choose mixed-use communities to substitute walking for motoring is never fully captured in the trip generation phase.

Trip Distribution

In the forecast of travel flows, the handling of intrazonal travel is most problematic. Because four-step models have a regional focus, they deal crudely with travel within neighborhoods. All households and jobs are treated as if located at a single point, the centroid of the zone; the local street network is reduced to one or two “centroid connectors” to the external street network; and for purposes of trip distribution, the durations of all trips within a TAZ are assumed to be the same, typically set at one half to two thirds of the travel time to the nearest neighboring zone. For suburban TAZs, average travel times can be long, beyond what most Americans will devote to walking. For

urban TAZs, however, average trip durations can be less than half the travel time to the nearest neighboring zone. And factors that encourage walking, like fine-grained land use mixes, local street connectivity, and pedestrian amenities, do not influence intrazonal trip estimates. Thus, the number of intrazonal trips tends to be underpredicted in more densely developed areas, and the mode-choice models that are informed by trip distribution end up predicting that the vast majority of intrazonal trips will be made by private vehicle.

Mode Choice

Most mode-choice models suffer from some degree of misspecification. Because household surveys which inform four-step models often exclude walk and bike trips, non-motorized options are usually missing altogether from these models. Moreover, they generally use attributes of trip interchanges (i.e., comparative travel times by mode) as opposed to attributes of places (i.e., land uses at trip origins and destinations) to predict which mode travelers will use.

Even when factors like land use densities are included in mode-choice models, they do a poor job of capturing the potential ridership benefits of smart-growth initiatives such as TOD, again because of the relatively coarse spatial grain of the data. Studies consistently show that transit usage decays exponentially with distance from a station. Concentrating housing and employment within several hundred feet of a rail station will produce far more riders than placing the same amount of development a half-mile away (Bernick & Cervero, 1997).

Other Elements of Travel-Demand Forecasting

Few travel forecasting models include a step for allocating predicted trips by time of day, instead assuming set portions (e.g., 12%) will occur during the peak hour, varying (if at all) only by facility or area type. They fail to account for the phenomenon of peak spreading, in which people shift departure times from the peak hour to the shoulders of the peak as congestion increases with density and intensity of land use. Even among areas that do model time of day, such as metropolitan Portland and the San Francisco Bay Area, none account for the potential “de-peak” effects of mixed land uses. Placing a fitness center next to a suburban office building, for example, will prompt some office workers to return home at 7 p.m. after a workout, instead of at 5 p.m. Either source of peak spreading will reduce loads on nearby highways, lessening the need for capacity expansions.

Traffic assignment is also fraught with problems. The coarse level at which traffic assignment occurs reflects the

regional focus of four-step models. Local and sometimes even collector streets are not coded as links on digitized highway networks, meaning all the trips they carry, including those by bicycle and foot, can only be assigned to one or two major facilities, the centroid connectors.

Lastly, the fact that the models usually lack dynamic feedback loops between travel assignment and land use allocation perpetuates car-based planning. Theory suggests that if corridors are crowded by large volumes of traffic, future growth will seek less congested axes. Yet modelers rarely reallocate future population and employment to transit station areas or urban infill sites in response to worsening highway conditions.

Model Enhancements

Although the flaws listed above are significant, progress has been made in recent years on modifying components of four-step models to reflect the possible travel-reducing impacts of smart growth. Models are also being reworked so they can interact with the SUMMIT user-benefits model the Federal Transit Administration (FTA) uses to assess proposals for New Starts, the primary federal program supporting new capital investments in transit guideways. Disaggregate models like UrbanSim show promise (Waddell, 2000, 2002). They predict land use and transportation changes as results of the predicted behavior of individual households, businesses, and developers. To date they have been applied mainly to compare regional versus neighborhood impacts. And some regions, like Columbus (OH), Los Angeles, Denver, and Sacramento, are shifting to models that predict travel activities throughout the day as parts of multileg tours (PB Consultant, Inc., 2003). Tour-based models, proponents hold, better capture the extent to which mixed-use neighborhoods promote walking, bicycling, and transit trips. Such models, however, are still largely in the developmental phase.

MPOs that have been particularly proactive in enhancing four-step models include those from metropolitan Dallas, Portland, Sacramento, and Austin, and the San Francisco Bay Area. Four of their refinements are particularly relevant here: auto ownership models, pre-mode choice models (that estimate walk and bike trips), intrazonal estimates as supplements to trip distribution models, and respecified mode-choice models.

The Austin MPO estimated auto ownership models that captured the tendency of those living in compact, transit-oriented settings to own fewer cars (Marshall & Grady, 2005) and then used these lower estimates to predict trip generation and mode choice. In Portland,

Oregon, planners used a "pedestrian environment factor" that gauged walking quality (as a function of ease of street crossings, sidewalk continuity, street connectivity, and topography) to estimate the utilities of owning zero, one, two, and three or more vehicles, also as an input to trip generation and mode choice. Gainesville, Florida's carshedding model reduced the probability of owning two or more cars as regional access to jobs and sidewalk coverage increased (Ewing & Tilbury, 2002).

It is also increasingly common to add a model step that predicts nonmotorized travel (walk or bike) prior to mode choice. Austin's "pre-mode choice" model predicts that walking increases with higher housing, retail, and intersection densities and when jobs and housing are balanced (Marshall & Grady, 2005). Modelers in Portland and the San Francisco Bay Area use a two-step (nested) process to estimate the split between motorized and nonmotorized trips first, and then divide motorized trips between automobile and transit.

Advances have also been made in handling intrazonal trips. Gainesville, Florida's, trip distribution model increases the share of trips that occur within a TAZ as population densities, land use mix, street network intensities, and walkability indicators increase (Ewing & Tilbury, 2002). Many areas now refine trip distribution estimates by including a feedback loop that redistributes trips away from congested corridors following traffic assignment, as required by the U.S. Environmental Protection Agency's (EPA's) transportation conformity rule.

Where mode-choice models have been respecified to reflect influences of place-based variables like mixed land uses and residential densities they have been particularly useful for testing smart-growth scenarios. Recent studies of Montgomery County, Maryland (Cervero, 2002), and Austin, Texas (Marshall & Grady, 2005), found that such built-environment variables offer significant marginal power to explain tri-modal choice. Montgomery County's mode-choice model for home-to-work trips includes five predictors that reflect pedestrian and bicycle friendliness: amount of sidewalks, land use mix, building setbacks, bicycle infrastructure, and transit stop conditions.

Lastly, regions like Sacramento have accounted for the influences of traffic congestion on the location of activities through dynamic feedback loops between land use allocation and travel-demand models. Including land use feedback lowered vehicle miles traveled (VMT) estimates of smart-growth scenarios by more than 5% relative to estimates generated without feedback loops (Rodier, Johnston, & Abraham, 2002).

Alternative Approaches: Post-Processing and Direct Models

In addition to these model enhancements, there are other new approaches to probing the travel impacts of smart growth. Most are "first cut" sketch-planning tools that may do a better job of picking up some of the nuanced relationships between smart growth and travel demand than even enhanced large-scale models. Often, they can also generate demand estimates quickly and economically.

Post-Processing

Post-processing normally involves pivoting off of four-step model outputs, using elasticities to account for effects (such as those of land use variables) not specifically accounted for in models. This is sometimes done for expediency, given the considerable time and cost of compiling local data and recalibrating large-scale models. The city of San Luis Obispo, California, recently used post-processing to "tweak" a countywide four-step model to reflect local conditions (Fehr & Peers, 2005b). The city used local data to calculate elasticities reflecting how density, land use diversity, and design influence trip generation.

To date, post-processing has been used more often to reflect the impacts of transportation demand management (TDM) and intelligent transportation system (ITS) strategies than to show the influences of smart growth. The Federal Highway Administration TDM evaluation model, for instance, uses a pivot-point approach to modify mode choice to reflect the travel-time and cost savings of carpooling, flex-time, and other TDM strategies. Emissions post-processors, such as MOBILE 6, account for variations in speed by time of day and vehicle type to refine air-quality estimates from the traffic assignments of four-step models.

Post-processing was used to examine the travel impacts of redeveloping the Atlantic Steel site in central Atlanta (Walters, Ewing, & Schroeder, 2000). The Atlanta region's nonconformity with federal clean air standards held up progress on the project by freezing federal financial assistance for supporting improvements, including a multi-modal bridge to a nearby subway station. The developer argued that the proposal for mixed-use infill near rail transit would yield air quality benefits by housing population that would otherwise live less centrally, and be more car-dependent. Consultants hired to estimate the travel impacts of the Atlantic Steel proposal quickly realized that the Atlanta Regional Commission's four-step model was not up to the task, and proceeded to post-process its outputs. They justified adjusting modeled trips and mode-choices using studies from the San Francisco Bay Area

(Cervero & Kockelman, 1997), metropolitan Portland, and other areas (Ewing & Cervero, 2001), that found density, land use diversity, and pedestrian-friendly designs reduced vehicle trip rates and VMT. The consultants concluded that the Atlantic Steel project would produce up to 52% fewer trips than the same development in a green-field location. The post-processing results were pivotal in EPA's decision to give the Atlantic Steel project a green light.

Post-processing was also used to predict daily traffic for various land use and transportation options for the planned Legacy Parkway west of Salt Lake City (Fehr & Peers, 2004). The U.S. Court of Appeals, 10th Circuit, remanded the Parkway's Final Environmental Impact Statement on grounds that mass transit options had not been fully explored as part of a "shared solution" for handling projected traffic increases along this busy north-south corridor. To incorporate the latest research on the travel impacts of TOD, transit service enhancements, and TDM, forecasts from the Wasatch Front Regional Council's four-step model were post-processed. Specifically, elasticities from national research on "Traveler Responses to Transportation System Changes" were used to pivot off of four-step forecasts to refine estimates (Kuzmyak, Pratt, Douglas, & Spielberg, 2003). In the car-oriented suburbs of Salt Lake City, these adjustments resulted in a less than 1% increase in 2020 transit ridership forecasts along the Legacy corridor.

Finally, post-processing was used to assess an alternative growth scenario for the Baltimore region (Kuzmyak, 2006). The scenario improved the jobs/housing balance by moving additional households into an employment-rich corridor, and assumed a mixed-use pattern would develop within the corridor. Post-processing household vehicle ownership and VMT models were developed from recent household travel survey data. The models used a measure of access to jobs at the TAZ level to gauge regional accessibility, and sub-TAZ land-use-mix and connectivity variables to measure local accessibility. Initially, the Baltimore Metropolitan Council's conventional travel model was used to estimate the impact of the household shift and new transit service, and then elasticities from the VMT model were applied to post-process results. While the travel model showed acceptable sensitivity to new transit service, it was curiously insensitive to the relocation of households. In the end, plausible forecasts were obtained by simply applying vehicle ownership and VMT models to TAZ-level forecasts of vehicle ownership and household VMT for the existing land use plan.

Direct Modeling

Another alternative to the four-step method is *off-line* or *direct* modeling of demand. As applied to date, this has been done using stand-alone models to directly estimate travel for neighborhoods, most notably ridership for rail proposals and TODs. Direct models estimate ridership as a function of station environments and transit service features rather than using mode-choice results from large-scale models. This provides fine-grained output suitable for studying relationships between ridership and the built environment and transit services. These models also capture dynamics that bigger models miss, such as the effects of self-selection on transit usage and the tendency of patronage to decay exponentially with walking distance from a station.

Because direct models predict demand for a specific node or point rather than for a corridor, some variables normally found in mode-choice models, such as comparative travel times and prices of transit versus auto travel, are conspicuously absent. However, some of the direct models do include the accessibility of station-area residents to jobs and shops by transit versus by car, retaining this aspect of the relative performances of the competing modes.

The direct models generally have small samples since an observation is normally a transit station. Thus degree of freedom constraints often limit the number of variables that can be included, and may preclude the inclusion of interactive terms. It is because of these limitations that direct models should be classified as sketch-planning tools. They can predict the likely orders of magnitude for consequences of a land use scenario, suitable as a first-cut analysis, but they cannot replace fully specified travel demand models.

Fehr & Peers (2005a) write the following, in defense of the direct modeling approach for studying rail options in Boise, Idaho:

The feasibility—and fundability—of a new transit service hinges on ridership projections. Rail ridership is traditionally forecast with region-wide travel demand models. These generally represent a region's transportation network and land use at an aggregate scale. These models are often unresponsive to changes in immediate station-area land use and transit service characteristics. Where transit trips represent a relatively small percentage of the travel considered in region models, even a well-calibrated mode choice model can have difficulty reasonably forecasting location-specific ridership simply because they cannot easily incorporate micro-scale (sub-TAZ) station-area characteristics that affect transit use. Direct ridership models . . . are a precise, quick-response alternative. They are directly

and quantitatively responsive to land use and transit service characteristics within the immediate areas of prospective stations. (p. 31)

Examples

Over the past decade, I have been involved in developing direct models of ridership for three U.S. fixed-guideway transit proposals, all involving TOD scenarios. The ability to produce credible forecasts in a short period of time was an important advantage in each instance.

Direct Modeling of Charlotte's Transitway/TOD Scenarios

In 1998, voters of Charlotte-Mecklenburg County, North Carolina, were asked to approve a half-cent sales tax increase to finance fixed-guideway transit improvements spread over more than 20 years and costing more than one billion dollars. Concerned that unchecked sprawl and traffic snarls threatened the region's long-term economic health, civic leaders embraced high-quality transit both to meet mobility needs and to shape regional growth. Many also felt that the only way to justify costly investments in rail or dedicated busways in auto-friendly Charlotte would be to channel significant shares of future growth to transit hubs and stations.

Before the sales tax referendum could be brought before area voters, a 2025 Transit/Land Use Plan needed approval by Charlotte's City Council and Mecklenburg County's Board of Supervisors. The plan had to be backed by credible ridership forecasts and cost estimates. However, the region's four-step model, calibrated using data from the 1960s, was incapable of forecasting the ridership impacts of TOD. The region's TAZs were too large to use them to model transit villages, typically half-mile-wide walkable rings around stations, and the mode-choice model included no land use variables.

We selected the direct modeling approach as a second-best alternative to four-step model enhancement. Since there were no local experiences with fixed-guideway passenger services on which to draw, we turned to a national database generated under the Transit Cooperative Research Program (TCRP) H-1 study, "Transit and Urban Form" (Parsons Brinckerhoff Quade & Douglas, Inc., Cervero, Howard/Stein-Hudson Associates, Inc., & Zupan, 1996). The TCRP database contained information on land use densities, transit operational and design features, and daily boardings for 261 stations and their environs drawn from 11 U.S. and 2 Canadian regions with recent light-rail transit (LRT) systems or extensions.

The left-hand columns of Table 1 forecast daily station boardings using the national model calibrated in the TCRP H-1 study. The original model appeared underspecified, however. Most notably, it included no measure of transit service levels, although such a variable is often the strongest single predictor of ridership. This meant that other variables, most notably population density, included the influence of this important omitted variable. Since denser areas typically receive more frequent transit service, the TCRP model likely exaggerated the effects of residential densities on ridership. We re-estimated the model, including both a measure of service frequency and dummy variables (not shown), to statistically capture the unique effects of each municipality from the national database on ridership rates.

The right side of Table 1 shows the revised model (Cervero, 1998). Not only did it produce a better statistical fit, but equally important, it captured a truer relationship between population density and ridership, consistent with past research. Including the service-frequency variable "number of inbound trains in peak hour" precluded "population density" from appearing as the source of this influence as well as its own. Whereas the TCRP model estimated the point elasticity between ridership and residential densities

to be 0.592 (as reflected by the coefficients on the log-log model), the revised model produced a far more conservative estimate of 0.192 (i.e., a 10% increase in residential density was associated with a 1.9% increase in transit boardings, all else being equal).

We then used post-processing to fine tune the estimates. For example, the direct model did not capture the influences of suburban employment on ridership, since the TCRP database contained employment data only for central business districts. Based on experiences from rail-served cities in California, metropolitan Washington, Toronto, and Edmonton, we conservatively assumed that 9% of commute trips made by employees working in station areas outside of downtown Charlotte would be by fixed-guideway transit (Bernick & Cervero, 1997; JHK and Associates, 1989).

We also made refinements to the region's four-step model. Most notably, we used a car-shedding equation from South Florida to lower estimates of average autos per household in TAZs located in transit corridors (Ewing, 1998). The model showed that higher combined population and employment density reduced the odds of owning two or more vehicles twice as much as it reduced the odds of owning a single vehicle. Thus, knowing that higher densities

Table 1. Direct models estimating natural log of daily station boardings.

Variable	TCRP model		Revised model ^a	
	Coefficient	<i>p</i>	Coefficient	<i>p</i>
Station in CBD (0 = no, 1 = yes)	b	b	0.735	.000
Terminal station (0 = no, 1 = yes)	1.031	.000	0.855	.000
Park-and-ride (0 = no, 1 = yes)	0.419	.023	0.410	.000
Feeder bus services (0 = no, 1 = yes)	0.842	.000	0.731	.000
Catchment size: Natural log of distance to nearest adjacent station	0.892	.000	0.197	.000
Distance to CBD: Natural log of miles between station and CBD along shortest light-rail route	-0.597	.001	-0.209	.001
Population density: Natural log of persons per gross acre within ½ mile of station	0.592	.001	0.192	.000
Service level: Natural log of number of inbound trains in A.M. peak hour (7 to 8 a.m.)	b	b	0.594	.000
Interaction of CBD employment and density: (Employees per gross acre within ½ mile of station) x (natural log of employees/1000)	.00110	.000	.000332	.028
Constant	5.390	.000	4.873	.000
<i>N</i>	261		225	
<i>R</i> ²	.536		.771	
<i>F</i> (prob.)	46.5 (<i>p</i> < .001)		86.7 (<i>p</i> < .001)	

Notes:

- a. Fixed-effect variables for cities were included in the revised model, but are not shown here.
 b. Not included in the original TCRP model.

reduced the number of households owning second cars, we calculated revised averages for autos per household using the following pivot-point formula to predict trips originating and ending in TAZs in transit corridors under TOD scenarios.

$$\left(\frac{\text{autos}}{\text{household}}\right)_{\text{tOD}} = \left(\frac{\text{autos}}{\text{household}}\right)_{\text{trend}} \times \left(\left(\text{elasticity} \right) \times \left(\frac{\text{density}_{\text{tOD}}}{\text{density}_{\text{trend}}} \right) + 1 \right)$$

In the formula, “trend” refers to the original model result, and “elasticity” to the observed percent change in autos per household per one percent change in density.

The projections obtained from the direct model, which showed higher-than-expected ridership, were the result of assumed high-quality transit services and future TOD. Higher ridership projections contributed to the draft long-range plan being approved and eventually helped the dedicated sales tax succeed with voters in 1998. In the ensuing years, Charlotte-Mecklenburg has built five radial transitways. A historical trolley line opened several years ago, connecting the upscale in-city South End neighborhood to downtown (see Figure 1). A 10-mile light-rail line is now under construction, having earned a “highly recommended” rating by FTA, and planned busways along the southeast and northeast corridors are in the final design stage.

Modeling tBART and TOD

In an effort to channel growth spilling from the eastern fringes of the San Francisco Bay Area into California’s central valley, a 55-mile extension of the Bay Area Rapid Transit (BART) system, called tBART, was proposed in 2001 (see Figure 2). BART’s board of directors decided to estimate a direct ridership model for several reasons. First, they wanted an analysis of tBART’s feasibility quickly, and it would have taken considerable time to generate forecasts using the region’s sophisticated, but data-hungry, travel model. Second, BART’s board also wanted a “scan” of alternative technologies and service concepts, including lower-cost diesel multiple unit (DMU) systems, but the regional travel-demand model was not designed to separate out the effects of different rail technologies on usage. Finally, the board wanted ridership estimates for each of the proposed 25 stations. Given the region’s several decades of experiences with heavy rail (i.e., BART) and DMU-like services (on the Caltrain peninsula commuter-rail line) it would be possible to measure the effects of factors like station-area density and technology type on ridership empirically and use them in a micro-scale model.

Table 2 presents the estimated tBART model (Walters & Cervero, 2003) using data for the 68 existing BART and Caltrain stations.² Because it is a log-log regression equation,

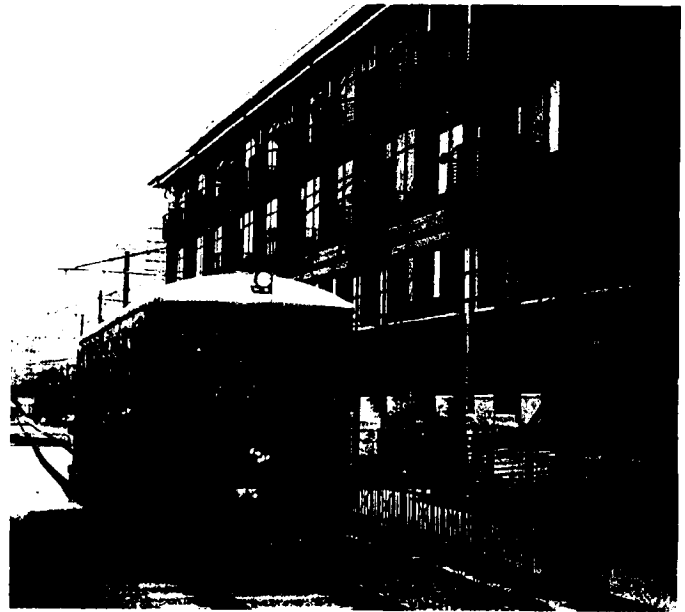


Figure 1. Historic trolley connects renovated townhomes in the rejuvenated South End neighborhood to downtown Charlotte.

the coefficients represent elasticities. Consistent with theory, Bay Area ridership levels were most sensitive to service levels. The high positive coefficient on the “technology” variable revealed that ridership at BART stations tends to be systematically higher than at Caltrain stations, even controlling for factors like the number of people in the expected catchment area. This reflects BART’s superior level of regional connectivity (190 directional rail miles compared

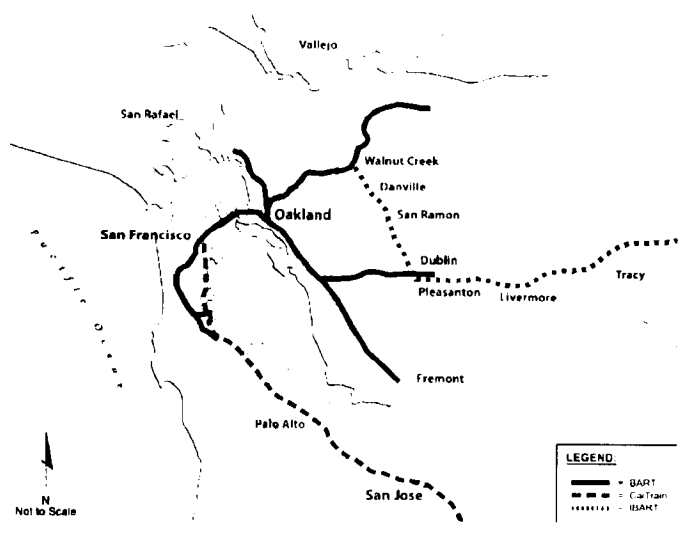


Figure 2. Proposed tBART extension in the East Bay of San Francisco–Oakland.

to Caltrain's 153 in 2000), more extensive midday operations, and greater station amenities. Feeder-bus service levels had a moderate influence on ridership; on average, every 10% increase in peak feeder buses was associated with a 2.9% increase in passenger boardings. Parking supplies exerted weaker effects. The elasticity of 0.233 for station-area density was fairly close to that generated using the national TCRP database (shown in Table 1).³

The direct model projected that 2020 ridership for planned tBART stations would fall in the middle range of existing Caltrain stations and generally below those of BART. We projected that TOD scenarios that would double the trend-line projections of station-area densities would increase estimated daily ridership between 11 and 17% compared to the trend-line forecasts. These numbers match the ridership "bonus" attributable to TODs like Pleasant Hill in the San Francisco Bay Area (Cervero, Murphy, Ferrell, Goguts & Tsai, 2004).

Although fiscal realities prompted BART's board to set aside the tBART concept at least temporarily, it was gratifying that BART planners as well as regional modelers accepted the direct modeling approach as a credible basis for generating first-cut ridership estimates for alternative service and land-use scenarios. Interestingly, the lead consultants for the tBART study, Fehr & Peers, used the Bay Area direct model to generate first-round estimates of ridership for heavy-rail options in Boise, Idaho, presumably believing that relationships between station-area environments and usage are similar even in different metropolitan settings.

Direct Modeling of St. Louis MetroLink's South Extension

St. Louis's 28-mile MetroLink light-rail system has been a ridership success, in part due to smart routing. With Lambert International Airport at one end and Scott Air Force Base in southern Illinois at the other, MetroLink interconnects numerous "all-day/all-week" trip generators: several large downtown sports venues, three universities, two medical centers, an active riverfront and gaming port, and colorful Union Station, in addition to the international and military airports. But MetroLink has so far had little effect on urban form.

Several extensions to the MetroLink system have been proposed as part of a smart growth campaign, but the preponderance of growth around St. Louis over the past decade has occurred along highway corridors and in Clayton, an edge city without light-rail services. Southern St. Louis County is predominantly single-family homes, but local planners felt achieving transit-oriented growth in the southern suburbs was possible. They also expected ridership forecasts that included the effects of planned TOD to be essential if the MetroLink South extension they hoped for was to be competitive for federal New Start funds.

Local planners had little faith that the region's traditional four-step model could tease out the ridership implications of TOD. Working with the project's lead consultant, I estimated an off-line forecasting model using data on ridership, station attributes, and neighborhood characteristics for St. Louis MetroLink's 27 existing stations (Cervero, 2004).

Table 2. Direct model estimating the natural log of a.m. peak-hour station boardings, San Francisco Bay Area, 2000.

Variable	Coefficient	<i>p</i>
Station-area densities: Natural log of population and employment within ½ mile of station	0.233	0.008
Catchment populations: Natural log of population of defined station catchment area (based on historical evidence on where passengers come from)	0.021	0.740
Service frequency: Natural log of number of train cars in one direction (6 to 9 a.m.)	0.477	0.012
Feeder bus services: Natural log of number of feeder buses arriving at station (6 to 9 a.m.)	0.287	0.000
Parking: Natural log of number of station parking spaces	0.038	0.133
Technology: 1 = heavy rail (BART); 0 = commuter rail (Caltrain)	1.576	0.000
Constant	2.400	0.026
Summary statistics		
<i>N</i> = 68		
<i>R</i> ² = 0.898		
<i>F</i> = 45.2 (<i>p</i> < .001)		

My off-line St. Louis model operated on the principle that ridership could be estimated by establishing relationships with predictive variables that captured three transit submarkets:

1. *Walk-on riders*, indicated by activities within one half mile of the station. I expected variables related to population and employment density, mixed land uses, urban design, and roadway provisions in the vicinity of stations to potentially predict this submarket.
2. *Feeder-bus riders*, indicated by the frequency of feeder bus service.
3. *Park-and-ride riders*, or those who live or work at distances too great to walk or bus easily to the station, indicated by whether or not the station was a terminal station and by its supply of parking.

Table 3 presents the best-fitting regression equation that captured the three submarkets, estimated from data for the 27 existing MetroLink stations.⁴ Because of the small number of observations and multicollinearity, I estimated a parsimonious model containing two land use variables (population density and an index of land use mix) that

captured walk-on demand, a variable that gauged feeder-bus-access potential, and two station attributes (parking supplies and terminal station status) that accounted for park-and-ride market potential.⁵ While variables measuring population and employment accessibility via transit versus highway yielded the expected positive signs, they were too collinear with the stronger density predictor to enter the model. Both linear and log-log equations produced good fits, although the linear model, presented in Table 3, had the strongest predictive powers. Point elasticities from the log-log model formulation are shown on the right-hand side of the table.

Table 3 reveals that MetroLink ridership rises with housing density: Raising density within a half mile of a station by one dwelling unit per gross acre increases weekly boardings by nearly 1,100. The log-log model estimate of the point elasticity of ridership with respect to housing density was 0.145. The model further shows that a neighborhood with maximally mixed land use (i.e., with uses evenly spread among six use categories) averages nearly 3,750 more weekly boardings than does one that is single-use, all else being equal.

St. Louis planners expressed concern that the absence of TOD experiences in the St. Louis area would make the

Table 3. Direct model estimating weekly boardings at St. Louis MetroLink stations, 2000.

Variable	Linear model		Log-log model
	Coefficient	<i>p</i>	Elasticities
Housing densities: Number of dwelling units per gross acre within ½-mile radius of station	1,090.44	0.580	0.145
Mixed land use index: Mixed-use entropy index within ½-mile radius of station ^a	3,747.08	0.351	0.043
Feeder bus services: Number of bus routes arriving at station (6–9 am)	671.54	0.104	0.200
Parking supplies: Number of park-and-ride spaces at station	6.87	0.043	0.045
Terminal station: 0 = no; 1 = yes.	8,883.99	0.041	0.987
Neighborhood vehicle ownership levels: Mean vehicles per occupied housing unit within ½ mile of station	-9,830.91	0.007	-1.102
Constant	11,916.9	0.016	—

Summary statistics, linear model

$N = 27$

$R^2 = 0.638$

$F = 20.4$ ($p < .001$)

Note:

$$a. \text{ Mixed-use entropy (within } \frac{1}{2}\text{-mile ring)} = -1 \times \left(\frac{\sum_{i=1}^k p_i \times \ln(p_i)}{\ln(k)} \right)$$

where: p_i = proportion land in use i of total of all land; and $k = 6$ categories of land use (single family housing units, multifamily housing units, basic commercial employment, service employment, industrial employment, public employment).

ridership projections shown in Table 3 less credible. Much of the existing MetroLink system operates on disused freight lines where development has reached maximum build-out capacity. The MetroLink South extension, on the other hand, would mainly operate in existing road rights of way and, in some cases, in corridors with new development opportunities. To reflect these different conditions the decision was made to generate baseline and TOD forecasts from both the locally derived model (shown in Table 3) and the national TCRP model estimated for Charlotte-Mecklenburg (shown in Table 1) and to use averages of the two as midpoint estimates of weekly boardings in 2025. The national TCRP model captured more favorable ridership conditions (e.g., light-rail stations in high-growth areas, nonfreight corridors, etc.). The local model offered the advantage of embedding local circumstances, like the regional economic conditions and system-wide transit service attributes, in the estimates. Using the combined results, the TOD scenario increased forecasted 2025 ridership between 8 and 21% above baseline estimates. This differential was substantially above that of the locally derived model and, in the view of local planners, lent credence to a policy of aggressively pursuing infill, mixed-use development near planned MetroLink South stations.

Policy Insights and Prospects

Off-line modeling provided a useful platform for testing TOD scenarios in three large U.S. metropolitan areas and is currently being applied in smaller metropolitan areas such as Boise, Idaho. Comparing model results offers insights into the potential ridership pay-off of concentrating development near rail stops. Notably, the ridership to density elasticities (percentage increases in rail boardings as residential densities increase by 1%) were substantial, and similar across the three analyses: 0.192 based on national experiences (from 225 LRT stations in 9 cities); 0.233 based on experiences in the San Francisco Bay Area (for 68 heavy and commuter rail stations); and 0.145 based on experiences in metropolitan St. Louis (for 27 LRT stations). The elasticity Fehr & Peers estimated with their recent off-line model using Sacramento data was even higher, at 0.300.

These figures are large compared to elasticities for private vehicle trips with respect to density in U.S. suburban settings, which average around -0.05 , and to those gauging the effects of land use diversity or design on walking (Ewing & Cervero, 2001). While one might argue that ridership to density elasticities obtained from direct modeling also incorporate the influences of mixed land uses and walkability, some studies suggest that people will patronize

transit regardless of the land use mix and walking quality of the station area, as long as it is relatively close by (Cervero, 1994; Lund, Cervero, & Willson, 2004).

The models suggest even greater effects on ridership when TOD is accompanied by service enhancements. Based on elasticity differentials, ridership was more than three times as sensitive to service frequency as to residential densities based on the national TCRP database; in the San Francisco Bay Area, daily boardings were more than twice as sensitive.

Post-processing and direct modeling approaches will only gain legitimacy if embraced by policymakers and their professional staffs. And they should be willing to do this because alternative modeling approaches like these complement, but do not substitute for, traditional four-step models. Off-line models are well suited to producing order-of-magnitude estimates of the travel-demand effects of smart growth scenarios. Thus, they should be used as sketch models. This is precisely how they were used in Charlotte, the Bay Area, and St. Louis, and for this reason they encountered no serious resistance. These modeling approaches, which are uniquely suited to predicting the consequences of smart growth's fine-grained design details, deserve a place in the toolbox of methods available to transportation planners.

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Notes

1. The four-step process consists of independent models whose outputs from one step provide inputs to a subsequent step: results of *trip generation* models (used to estimate numbers of trips produced by and attracted to zones, by purpose) feed into *trip distribution* models (used to estimate origin-destination flows between zones) which then feed into *mode-choice* models (used to apportion estimated flows between competing modes) which then feed into *travel assignment* models (used to load forecasted trips onto computer-generated networks of major streets and transit lines).
2. Besides reducing problems of multicollinearity, I chose a fairly parsimonious model to reduce the risk of error propagation. The chosen ridership models had reasonably good predictive accuracy based on current conditions.
3. Also of note was the fact that the populations of station catchment areas influenced ridership less than did station-area densities. While the "catchment population" variable was not statistically significant, BART planners wanted to include it in the equation to help with defining feeder bus and parking designs for tBART stations, viewing the loss of statistical efficiency from retaining this insignificant variable as less important than its usefulness for tBART spatial planning.

4. From the Sacramento direct model, elasticities of ridership as a function of other predictors were as follows: population density, 0.30; employment density, 0.21; parking supply, 0.11; and feeder bus service, 0.47.
5. While service levels are traditionally used to estimate transit ridership, the same train units generally serve all MetroLink stations for each directional run, meaning service levels were very similar across existing stations. Thus this variable was omitted as a predictor.

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