RESEARCH REPORT

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Subsidizing Transportation Network Companies to Support Commutes by Rail

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16. Abstract

We explore how rail transit's first- and last-mile issue might be addressed by partnering with transportation network companies (TNCs) like Uber and Lyft. The goal is to lure high-income commuters to shift from cars to TNCs and rail. We also explore how rail and TNC partnerships can improve travel for low-income commuters who currently rely on low-frequency bus service. We parametrically test subsidizing TNC fares for feeder services in the San Francisco Bay Area in an idealized fashion. Inputs such as the residents' value of time and vehicle ownership were taken from various local data sources. The communities that were selected for our study are served to different degrees by the BART rail system. We found that the optimal policy must be tailored to the characteristics of the community it serves. In dense, walkable communities with strong bus service near rail stations, TNC subsidies should be targeted to less-accessible neighborhoods and low-income commuters to not compete with bus transit and active modes like walking. For lower-density communities with limited dedicated bus feeder service, TNC subsidization can be applied more broadly, although disincentives, like increasing rail parking fees, must be considered carefully, because they can induce commuters to drive directly to work instead. We conclude with a discussion of how subsidies might be covered by reallocating existing resources in different ways.

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Rail transit and commuter rail are known to have a first- and last-mile problem. Because rail stations are spaced far apart, riders must often access them using another mode. Providing good access is often easier said than done depending on the feeder modes available and the local features of the community. Higher-income commuters drive to rail stations and pay to park (or omit using rail altogether and drive to work) while lower-income commuters rely on feeder buses or walking. We explored how subsidizing transportation network company (TNC) services, like Uber and Lyft, can reduce these inequalities by providing commuters efficient rail feeder service at a lower cost. From this research, we gained insights into how TNC subsidies can shift high-income commuters away from using their personal cars and into TNCs and provide a more efficient feeder option for certain lower-income commuters.

For this research, we modeled idealized communities where commuters reside as square areas with square street grids and connections to a central business district (CBD) by both rail and freeway. We populated the models with commuters who aim to maximize their individual daily net benefit by commuting via the lowest-cost mode. The commuters can travel to work by taking rail accessed either by walking, driving, feeder bus, or TNC, or they can drive to work directly. The commuters have randomly generated demographic characteristics drawn from census data distributions for four San Francisco Bay Area communities (the Lake Merritt neighborhood in Oakland, Richmond, Orinda, and the Glen Park neighborhood of San Francisco). Commuter characteristics for each community include residents' value of time, vehicle ownership rate, and desired workplace arrival time. A Monte Carlo procedure with thousands of iterations revealed the expected modal split for commuters under parametrically varied TNC subsidies.

Unsurprisingly, the models show that there is not a one-size-fits-all TNC subsidization policy for all communities. Subsidies need to be tailored to local conditions, such as commuter income level, population density, the availability and quality of alternative feeder modes, the distance to the CBD, and vehicle ownership rates. We can make the general claim, however, that an 80–90 percent TNC subsidy paired with a more modest increase in rail parking fees of 30–40 percent induced more than half of all the commuters to shift from driving to rail to using a TNC instead.

A negative effect does emerge from increasing rail parking fees. Higher-income commuters who drive to rail often shift to driving directly to the CBD rather than use a TNC feeder service. Additionally, no amount of TNC subsidy is great enough to persuade commuters who did not use rail initially to shift to rail. Instead, resources can be used to improve access to existing rail commuters and to those who cannot presently access rail.

In communities with high-quality feeder alternatives (like Oakland or San Francisco), such as frequent bus service or good walking infrastructure, subsidized TNC services ought to be used strategically to avoid competing with alternative feeder modes. Universally subsidized TNCs could lead to bus feeders losing ridership or induced vehicle use as commuters who previously walked to rail stations shift to TNCs. Targeting

TNC subsidies to commuters in need might be more beneficial. An equity-based subsidy can provide improvements to those in need without detracting from existing and more sustainable feeder modes. Those with higher priority include low-income commuters, those in neighborhoods without bus access, and groups who cannot walk to rail stations. We show that making fully subsidized TNC feeder service available can increase the average low-income commuter's individual daily net benefit by as much as 14 percent. Social service agencies and nonprofit community organizations might assist with funding or in distributing equity-based subsidies as part of their transportation assistance programs.

In lower-density communities (like Richmond and Orinda), TNC subsidies are shown to induce a large shift in commuters away from driving to rail and accessing it via TNCs instead. Pairing a 100 percent TNC subsidy with a 20–30 percent increase in rail parking fees induced up to 58 percent of commuters to shift. Funding for a full TNC subsidy might be covered in part by extra revenue from rail parking fees in the form of a cross-subsidy or by reallocating resources from low-ridership, low-frequency feeder bus lines. Additionally, the decrease in commuters who drive to rail reduces station parking demand, giving rail transit agencies the opportunity to put excess parking space to better use, for example, by leasing it out for transit-oriented developments or converting it into retail and housing. These redevelopments could generate additional revenue and further induce rail ridership.

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1. Introduction

Rail transit and commuter rail have a first-mile and last-mile (FMLM) problem (*1*–*3*). In an effort to keep trunk line speeds high, stations tend to be separated by long distances to reduce time lost due to stopping. This increases access cost for the user (e.g., rail transit stations are often spaced half a mile or more apart, and commuter rail stations by seven miles or more (*4*)). Stations must therefore rely on feeder systems to facilitate traveler connections, which might be achieved on foot, by driving, or via bus.

These feeder modes often have their own weaknesses. Walking is an option only for travelers whose trip origins and destinations reside a short distance from the station and who are physically fit. Rail stations might not even have infrastructure to support this. Additionally, housing near rail stations is typically priced higher than average, so living a walkable distance from a rail station is rarely an option for low-income individuals (*5*). Driving and paying a daily fee to park at a station is only an option for travelers with access to personal vehicles and the financial means to pay for parking. Creating available parking in close proximity to the rail station requires that land be suitably converted, with daily fees often priced below market value to induce transit ridership (*6*–*8*). Though driving to rail does result in travelers taking a public transit mode, the act of driving the first mile still has emission problems, especially because most vehicular greenhouse gas emissions are emitted when cold-starting a car (*9*). Feeder buses are only a viable option if high-frequency bus routes reside within walking distance of the traveler's origin or destination. If bus service is low frequency, or there are no timed transfers between bus and rail, a traveler could endure long commute times.

Hence, the FMLM problem for rail is so great that many commuters opt to drive directly from home to work, despite having to pay for tolls, gas, vehicle maintenance, and city parking. What results are inequities in which high-income commuters pay to drive to work, medium-income commuters drive to rail stations and pay parking fees, and low-income commuters are relegated to taking feeder buses or walking (sometimes lengthy distances) to access rail stations (*10*–*12*).

One tool to help address these inequities is to use transportation network companies (TNCs) like Uber and Lyft to provide FMLM service for rail transit. TNCs can travel at high speeds and provide on-demand, door-to-door service, similar to that of driving. Additionally, because TNCs are administered by independent contractors using their personal vehicles, their services can scale up or down based on market forces so that there can always be supply to meet demand, as distinct from buses, which have a more rigid supply framework. Prior qualitative research has also found that some higher-income travelers already use TNCs to connect to rail transit, so making this service available to all rail commuters via subsidies might improve its viability as a feeder option (*13*).

The goal of this research is to see to what degree TNC subsidies can help address the FMLM problem for rail transit. For higher-income commuters, we want to determine what level of TNC subsidization is necessary to shift them away from their personal vehicles to rail. For low-income commuters, we explore how subsidized

TNCs can provide a more efficient feeder option than buses or walking. We strive to achieve both goals without negatively impacting feeder bus ridership or active transportation modes.

We achieve these goals by developing models to describe four San Francisco Bay Area communities. The communities were first idealized as square areas, and commuter behavior was modeled using deterministic utility models. The idealizations were then populated with synthetic populations based on the communities' real-world characteristics and simulated using a Monte Carlo procedure to see which commute mode shifts occur under different subsidization policies.

Analysis of our model output shows that subsidizing TNCs can successfully shift up to 58 percent of commuters who previously drove their personal cars to rail stations to using a TNC feeder instead, although subsidization policies need to be customized to the unique features and needs of the community. The models show limited likelihood of commuters who drive to work (those who do not already take rail transit) shifting to a TNC feeder. But subsidizing a TNC feeder service does improve the average daily net benefit for low-income commuters.

In Section 2, we present the models that we have developed to study subsidization policies and our experimental design for parametrically testing subsidy levels. In Section 3, we describe the results of our subsidization tests applied to four different scenarios based on communities and transportation systems located in the San Francisco Bay Area. Section 4 offers a discussion of promising strategies for subsidizing TNC feeder service and next steps for this research.

2. Methodology

Continuous approximation (CA) models were developed to describe the feeder modes for a rail station in idealized communities where commuters reside. Deterministic utility models were used to model the costs and benefits of commuting by each available mode. Data representing the real-world transportation modes and demographic characteristics of four San Francisco Bay Area communities were used to simulate the commute mode selection for a synthetic population. By changing policy variables, such as the subsidization level for TNC feeder fare or the fee to park a personal car at a rail station, we test how commuter mode choice is affected under different influences.

2.1 Idealizations

Our case study is of an idealized metropolitan region with a central business district (CBD) that is connected to surrounding communities via a highway and a trunk-line rail system (see Figure 1). Each community is centered around the connector rail station, and commuters in the metro region use the rail station that is closest to them. The radius of a specific community R_l is equal to the maximum distance from which a commuter living in that town would travel to rail station l to commute by rail. The distance from a community's rail station to the CBD is L_l. Figure 2 illustrates an individual community with rail transit.

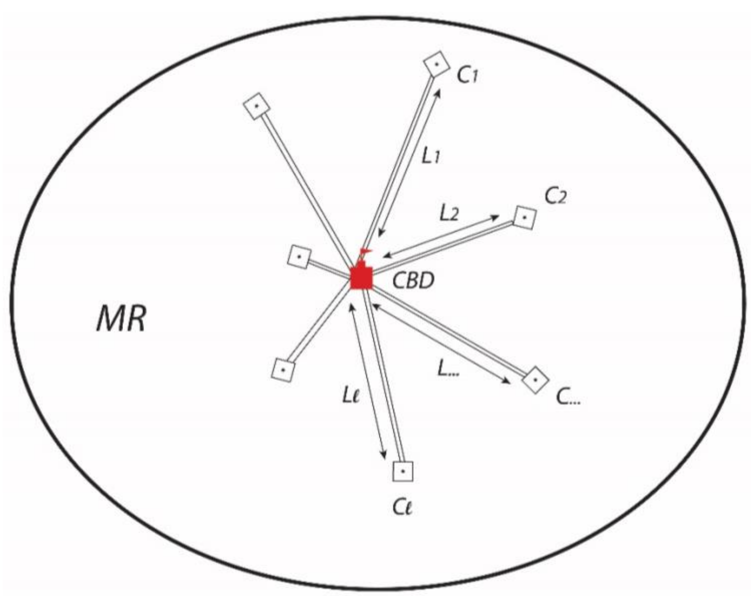


Figure 1. Idealized Metropolitan Region (MR) with Surrounding Communities (C) Connected by Trunk-Line Rail Service

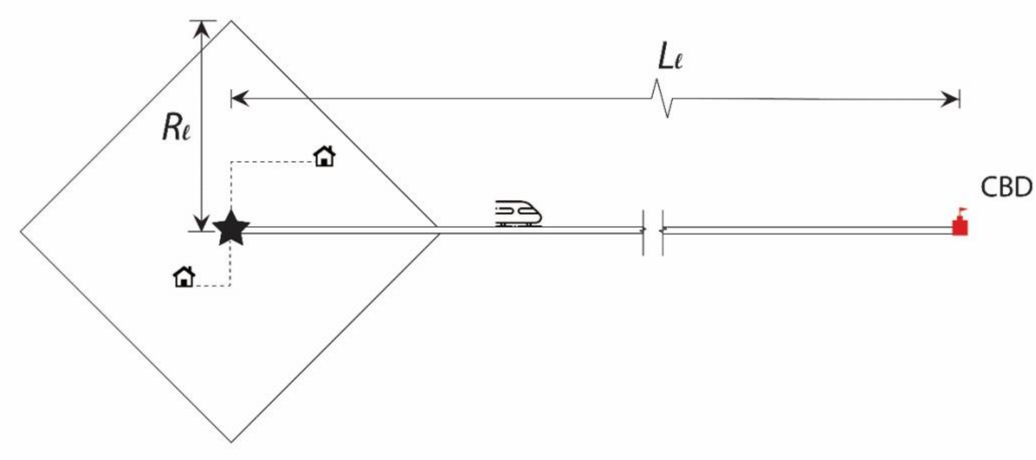


Figure 2. Single Idealized Community Connecting to the CBD with Trunk-Line Rail Service

Each community is also connected to the CBD by a highway that runs from one corner of the community to the CBD. For a community of radius R_l the length of the highway equals $L_l - R_l$ (see Figure 3).

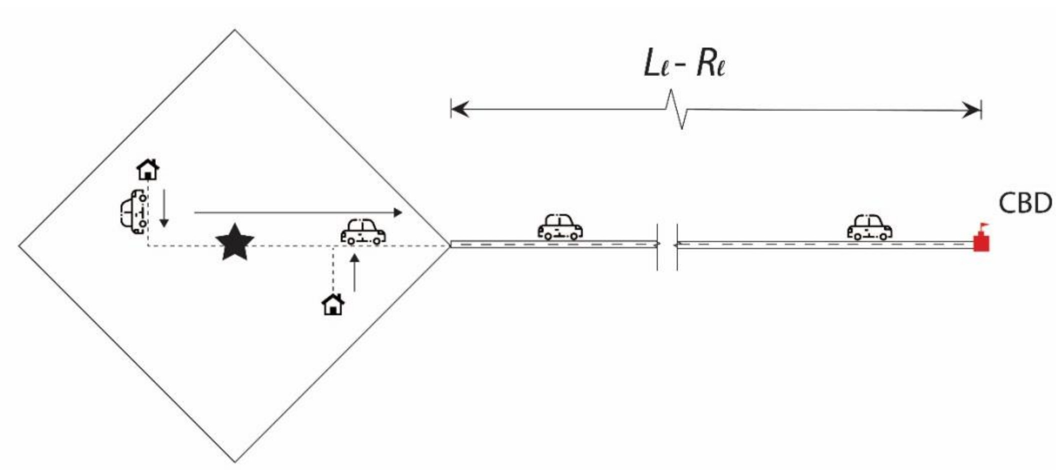


Figure 3. Single Idealized Community Connecting to the CBD with a Highway

Because the idealized communities are small, and the number of people commuting daily from them to the CBD is small compared to the flows of people in the metropolitan region, we assume that the commuters we are analyzing do not impact the level of congestion on the highways. That said, the commuters from our communities are affected by commute congestion on the highway. Similarly, we assume that there is ample capacity in the regional rail system. Because no commuter's mode choice from one community will affect the mode choice of a commuter in a different community, we can treat each community as independent from the others.

2.2 A Closer Look at One Community

To describe the details of our model, we shift our focus to one representative community and drop the subscript l. We model a community as a rotated square with side length $\sqrt{2}R$, within which is an infinitely dense grid of streets. We can represent the community as a Cartesian plane with the rail station at its origin and assign each commuter's home an (x, y) coordinate. Homes are homogeneously distributed over the area at density δ (people/km^2). All commuters' destinations (workplaces) are concentrated in the CBD, and commutes occur at rate λ (round-trips/person-hour). The density of commute trips per hour is λδ round-trips/km^2-hour.

The community is served by a hub-and-spoke style feeder bus system, with a common route running the horizontal length of the town and branches extending vertically in north and south directions (see Figure 4). Buses are scheduled with a headway of h_b hours, bus line branches are evenly spaced S km apart horizontally, and bus stops are spaced s km apart vertically. The number of branches per quadrant of the community is $n_{branch} = \max\left(1, \left\lfloor \frac{R}{S} \right\rfloor\right)$ and the number of stops on each j branch is $n_{stops,j} = 1 + \left\lfloor \frac{R-jS}{s} \right\rfloor$, where $\lfloor \cdot \rfloor$ is the floor operator. Commuters are assumed to walk to the nearest downstream bus stop on the closest bus line.

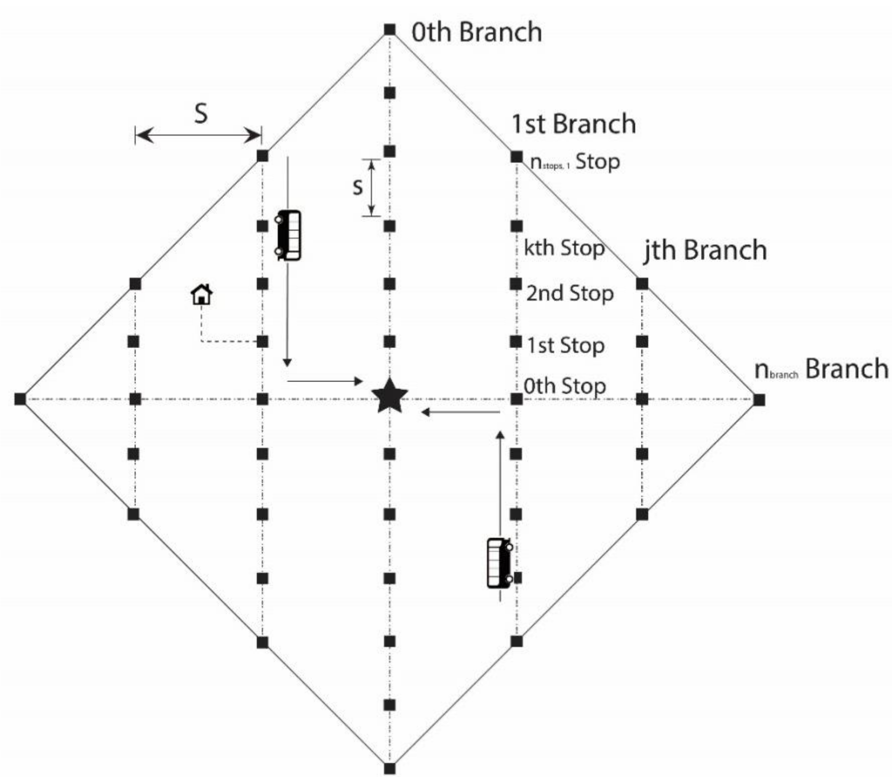


Figure 4. Hub-and-Spoke Feeder Bus System for a Community, with Example of Branch and Stop Labeling Schema in Upper-Right Quadrant

Commuters who travel by rail can reach the rail station in one of four ways: walking, driving, bus, or TNC feeder. Commuters who drive to rail pay a daily parking fee at the station. Commuters also have the option to drive directly to the CBD via the highway and pay for daily parking in the CBD and any highway tolls. Commuters are reasonably assumed to use the same commute mode for their morning and evening commutes.

When commuters reach the CBD, the time-cost associated with walking to their workplace is assumed small compared to the other parts of their trip, and thus is ignored in the model.

2.3 Net Benefit Approach to Mode Selection

Commuters receive a (positive or negative) net benefit related to commuting to work, comprised of the benefit received from going to work, less the costs associated with the round-trip commute (both morning and evening). We assume commuters are rational and seek to maximize their individual daily net benefit related to commuting, and therefore select the commute mode that results in the highest net benefit. Commuters are always able to take their preferred mode.

We use a building-block approach to construct the net benefit equations for each commute mode, as described below.

2.3.1 Commuter Benefit, *B*

For this model, we treat the value of the commute, B ($/day), as one-half of the commuter's daily earnings. We assume a commuter would not be willing to travel to work if spending more than half of their daily earnings on the round-trip commute and will only receive this benefit if they actually commute to work. The daily commute benefit is:

$$B = 4\beta$$

where β is the commuter's value of time ($/hr).

2.3.2 Cost of Rail to CBD, C_R

A commuter traveling to the CBD by rail experiences the time-cost associated with waiting for the next train at the origin station (on average, one-half the scheduled headway), the time-cost of riding the train, and the monetary cost of the fare. Thus,

$$C_R = 2\left(\beta\left(\frac{h_r}{2} + \frac{L}{v_r}\right) + c_r\right)$$

where C_R is the daily cost of taking rail to the CBD ($/day), h_r is the rail headway (hr/train), v_r is the average speed of the train (km/hr), and c_r is the one-way rail fare ($/trip).

2.3.3 Cost of Driving to CBD, C_D

Commuters who drive directly to the CBD first drive by surface streets to the entrance to the highway, and then travel the length of the highway. Starting from the commuter's home at (x, y), the total distance driven on surface streets is $d_{st} = |y| + R - x$. The distance driven by highway is $d_{hwy} = L - R$.

A commuter's daily cost of driving from their home to the CBD, C_D (\$/day), is therefore:

$$C_D = 2\left(\beta\left(\frac{d_{st}}{v_{c,st}} + \frac{d_{hwy}}{v_{c,hwy}}\right) + c_g\left(d_{st} + d_{hwy}\right)\right) + c_{toll} + c_{p,CBD}$$

where $v_{c,st}$ and $v_{c,hwy}$ are the speed of a personal car on surface streets and highway (km/hr), respectfully, c_g is the vehicle gas and maintenance cost (\$/km), c_{toll} is the toll to enter the CBD (\$/entrance), and $c_{p,CBD}$ is the daily parking cost (\$/day).

2.3.4 Cost of Walking to Rail Station, C_W

Commuters who access the rail station for their trip must travel a distance (via their access mode) equal to the L-1 norm distance from their home at (x, y) to the rail station at $(0,0)$, or a distance $d = |x| + |y|$.

Because commuters who walk to the station might experience less-than-satisfactory walking facilities, a unitless factor f_w is applied to capture the negative aspects of walking. The daily cost of walking to rail C_W (\$/day) is:

$$C_W = \frac{2\beta d f_w}{v_w}$$

where v_w is the commuter's walking speed (km/hr).

2.3.5 Cost of Driving to Rail Station, C_D

Commuters who drive to the rail station incur the time-cost of driving, the per-mile cost of gas and maintenance, and a per-day cost to park at the station, $c_{p,r}$ (\$/day). We assume minor time costs related to finding parking, walking from the parking lot to the rail station, etc. are contained in the per-day parking cost. The daily cost of driving to rail C_C (\$/day) is:

$$C_C = 2\left(\frac{\beta d}{v_{c,st}} + c_g d\right) + c_{p,r}$$

2.3.6 Cost of Taking Feeder Bus to Rail Station, C_B

Commuters who take a feeder bus to the rail station walk to the closest bus stop (j, k), where $j = \left\lfloor \frac{|x|}{S} \right\rfloor$ is the closest downstream branch to the commuter's home, and $k = \left\lfloor \frac{|y|}{s} \right\rfloor$ is the closest downstream stop on branch j. Their walking distance is $d_a = \big||x| - jS\big| + \big||y| - ks\big|$, and the distance by bus from bus stop (j, k) to the station is $d_b = jS + ks$.

A commuter who takes a feeder bus is expected to wait half a bus headway, and pays a bus fare c_b (\$/trip), bringing the daily cost, C_B(\$/day), to

$$C_B = 2\left(\beta\left(\frac{d_a f_w}{v_w} + \frac{h_b}{2} + \frac{d_b}{v_b}\right) + c_b\right)$$

where v_b is the commercial speed of the bus (inclusive of time lost serving bus stops) in km/hr.

2.3.7 Cost of Taking Feeder TNC to Rail Station, C_T

A commuter who takes a TNC feeder to get to the rail station is expected to have to wait a short time before the assigned TNC picks them up, t_w (hr/trip). We assume that a community contracts directly with a TNC service provider and can stipulate specific performance indicators to ensure that commuters receive a high quality of service, one of which might be the maximum time a commuter waits for the TNC to be picked up, t_{max}. If we assume that the contracted party agrees to pay a financial penalty for providing sub-par service (e.g., when $t_w > t_{max}$), the TNC provider is incentivized to provide service better than t_{max}. For this model, we conservatively set $t_w = t_{max}$.

The daily cost for a commuter to take a TNC feeder to rail C_T (\$/day) is:

$$C_T = 2(\beta\left(\frac{d}{v_{c,st}} + t_w\right) + c_t)$$

where c_t is the one-way fare for using the TNC feeder (\$/trip).

2.3.8 Commuter Mode Selection

From the mode-specific building blocks, the daily net benefit functions for an individual commuter taking distinct modes, including the option to not travel to work at all, can be constructed as:

1. **Walk to Rail:** $U_W = B - C_W - C_R$
2. **Drive to Rail:** $U_C = B - C_C - C_R$
3. **Bus to Rail:** $U_B = B - C_B - C_R$
4. **TNC to Rail:** $U_T = B - C_T - C_R$
5. **Drive to CBD:** $U_D = B - C_D$
6. **Does Not Travel:** $U_N = 0$

where U_m is the daily net benefit for taking mode m in \$/day.

The daily net benefit that a commuter selects, $\mathbb{U}$ (\$/day), is the largest for all available modes:

$$\mathbb{U} = max(U_W, U_C, U_B, U_T, U_D, U_N)$$

If the set of commute modes available is $M = \{W, C, B, T, D, N\}$, the mode the commuter selects $\mathbb{S}$ is

$$\mathbb{S} = \{m \mid m \in M, \mathbb{U} = U_m\}$$

2.4 Simulating a Synthetic Commuter Population

To simulate how a subsidized TNC feeder would impact commute mode choice, we use a Monte Carlo simulation to apply a subsidy policy to numerous synthetic populations of commuters and determine the expected mode shifts from the results of each iteration.

The socioeconomic, geographic, and transportation system properties of a community can be described by a collection of constants and probability distributions. The probability distributions for each community are: ν, the value of time distribution, found using U.S. Census data; and α, the desired workplace arrival time distribution, found using American Community Survey data. Vehicle ownership follows a Bernoulli distribution with parameter ζ, the vehicle ownership probability, found using U.S. Census data.

A synthetic population was created using the distributions to derive random, commuter-specific properties and applying the commuter mode selection process. A total $I = 2\delta R^2$ commuters are synthesized at each Monte Carlo iteration. Each commuter $i \in I$ is described by five random variables: the coordinates of the commuter's home, x_i and y_i; the value of time β_i; vehicle ownership status z_i, which equals 1 if the commuter owns a car and 0 otherwise; and the desired arrival time to the workplace a_i. The random draws are performed in the following manner:

$$\begin{aligned}
&x_i \sim Unif(-R, R)\\
&y_i \sim Unif(-R + |x_i|, R - |x_i|)\\
&\beta_i \sim \nu\\
&z_i \sim Bernoulli(\zeta)\\
&a_i \sim \alpha
\end{aligned}$$

To incorporate the vehicle ownership indicator z_i, we modify our daily net benefit equations by multiplying car-dependent commute mode costs by the factor $\big((1 - z_i) * G + 1\big)$, where G is a very large number. The daily net benefit equations for car-dependent modes then become:

$$\begin{aligned}
U_C &= B - \big((1 - z_i) * G + 1\big) * C_C - C_R\\
U_D &= B - \big((1 - z_i) * G + 1\big) * C_D
\end{aligned}$$

From the commuter's desired workplace arrival time a_i, and recent highway performance data (e.g., Caltrans' Performance Management System, PeMS), a conservative morning commuter departure time is back calculated. We assume each commuter begins work exactly at a_i, stays at the workplace 8 hours, and begins the evening commute at $a_i + 8$. The departure times at both ends of the commute can be used with highway performance data to determine the time-varying highway speeds (including expected congestion).

After each iteration, the proportion of commuters who select each mode is calculated, as well as the average value of time and daily net benefit for each mode. The same statistics are logged at each iteration for commuters without access to a personal car and for low-income commuters. Following a large number of iterations, averages are taken across all logged values to determine the expected mode share and socioeconomic statistics for each subsidization test.

2.5 Experimental Design

The San Francisco Bay Area (Bay Area) was selected as the metropolitan region of analysis for the large number of communities with varying population densities, income distributions, vehicle ownership levels, and public transportation services. The Financial District of the City of San Francisco was selected as the CBD for these tests because it is a top employment center in the Bay Area and contains a dense cluster of workplaces in a small area.

We selected four Bay Area communities with Bay Area Rapid Transit (BART) rail connections to the Financial District to simulate commuter populations and test different TNC subsidization policies. The four communities are illustrated in Figure 5. Values for each town's demographics, public transit service, and connections to the CBD were found using publicly available data. A summary of the communities' characteristics is presented in Table 1. The full tabulation of the parameter values used in the synthetic population simulations with their respective sources are provided in the Appendix.

Table 1. Characteristics of Bay Area Communities Selected for Model Representations

Community	Density	Average Income Level	Bus Transit System
San Francisco (Glen Park)	High	High	Muni Bus
Oakland (Lake Merritt)	Medium	Medium	AC Transit
Richmond	Medium	Low-Medium	AC Transit
Orinda	Low	Very High	County Connection

Figure 5. San Francisco Bay Area with Four Idealized Communities

The TNC fares used in all the simulations were based according to Lyft's 2023 fare structure for the Bay Area for a standard ride (single rider, normal sedan vehicle, no surge pricing or additional fees) (*14*). Each fare, c_t, was thus

$$c_t = \min\left(\max\left(\$2.24 + \$0.93 * d + \$0.40 * \frac{d}{v_{c,st}}, \$5.00\right), \$400\right) + \$3.60$$

For rides with a combined mileage- and time-based TNC fare lower than \$5, $c_t = \$8.60$ per trip was used. The expected TNC wait time, t_w, used in all scenarios was set at 5 minutes, because that is a realistic wait time for TNC service in California metropolitan areas (*15*). Caltrans PeMS data from March 2023 were used to calculate the time-varying highway speed for all commuters.

The first experiment was to establish a baseline mode share for each Bay Area community by running the Monte Carlo simulation with unsubsidized TNC fares and present-day rail station parking fees for comparison for all subsequent subsidization policies tested. Following this, we ran the simulation using different combinations of our primary policy variables: the percent subsidy for a single-trip TNC fare, which varied from a 0 to 100 percent subsidy; and the percent increase in the daily rail station parking fee, which varied from a 0 to a 100 percent increase.

With each policy combination, statistics for each commute mode were logged, including the proportion of low-income commuters who selected each mode. We defined low-income commuters as those whose income level makes them eligible for the Supplemental Nutrition Assistance Program/Electronic Benefit Transfer (food stamps) in California. For an individual, this is a gross income less than or equal to 200 percent of the federal poverty level (*16*). Thus, commuters with a value of time less than or equal to $12.89/hour were considered to be low income.

In addition to commuter income level and mode share, with each policy combination we explored the possibility of using the extra revenue earned from increasing the rail parking fee to assist with covering the TNC subsidy. The total dollar amount for the subsidy and the extra rail parking fee revenue were tracked during each simulation.

Following all policy combination tests, we calculated the rate of change per TNC subsidy amount and parking fee increase across modes for each Bay Area community. After we analyzed general trends related to TNC subsidization, we attempted to identify the optimal policy combination and customize it for the needs of each community. Our basis of selection was to identify policy combinations that maximally reduce personal car use, create minimal mode shift away from a feeder bus or walking, maximally increase the daily net benefit of low-income commuters, and are as close to cost-neutral as possible.

3. Application to Four Bay Area Communities

The modal split for the baseline case is presented first. Impacts from parametric tests of subsidy level follow. Impacts common to all four communities are presented in Section 3.2. Impacts unique to some of these communities are presented in Sections 3.3 and 3.4.

3.1 Baseline Modal Split

First, the modal split for all commuters in the baseline case is discussed. Then, in Sections 3.1.2 and 3.1.3, respectively, the modal split for low-income commuters and for non-car owning commuters in the baseline case are discussed.

3.1.1 Modal Split for All Commuters

Under the baseline scenario of no subsidies, commuters rely heavily on personal cars. The majority of commuters in the four communities travel to work by driving to the rail stations; see the dotted blocks in the barplots presented in Figure 6. Smaller but still substantial proportions drive directly to the CBD (the vertically striped blocks in Figure 6). Orinda is an outlier in this regard, because more than half its commuters (53 percent) drive directly to work. Although all communities had a portion of commuters in the baseline who walk to rail, San Francisco stands out for having the largest proportion (29 percent). Only Oakland and San Francisco have commuters who take a feeder bus to rail, with 13 percent and 2 percent, respectively. Because of the high average value of time for commuters in San Francisco and Orinda, a measurable percentage of them (9 percent and 3 percent, respectively) take a TNC as a feeder to rail even without subsidization. Richmond and Orinda both have a limited number of feeder modes other than a personal car. These communities therefore also have a small percent of commuters who choose not to travel to work (2 percent and 1 percent, respectively) because commuting is otherwise prohibitively expensive.

3.1.2 Modal Split of Low-Income Commuters

Low-income commuters typically either walk or drive to the rail station, depending on the level of vehicle ownership in their community and the walkability of the area surrounding the community’s rail station. Oakland low-income commuters are split evenly between walking and driving to rail, while 95 percent of low-income commuters in San Francisco walk. In Richmond, more than 50 percent of low-income commuters drive to rail, and in Orinda the percentage is 67 percent. A small proportion of low-income commuters choose not to travel in San Francisco and Oakland (3.5 percent and 5.5 percent, respectively), while a much larger percent find it too costly to travel in Richmond and Orinda (14 percent and 30 percent, respectively).

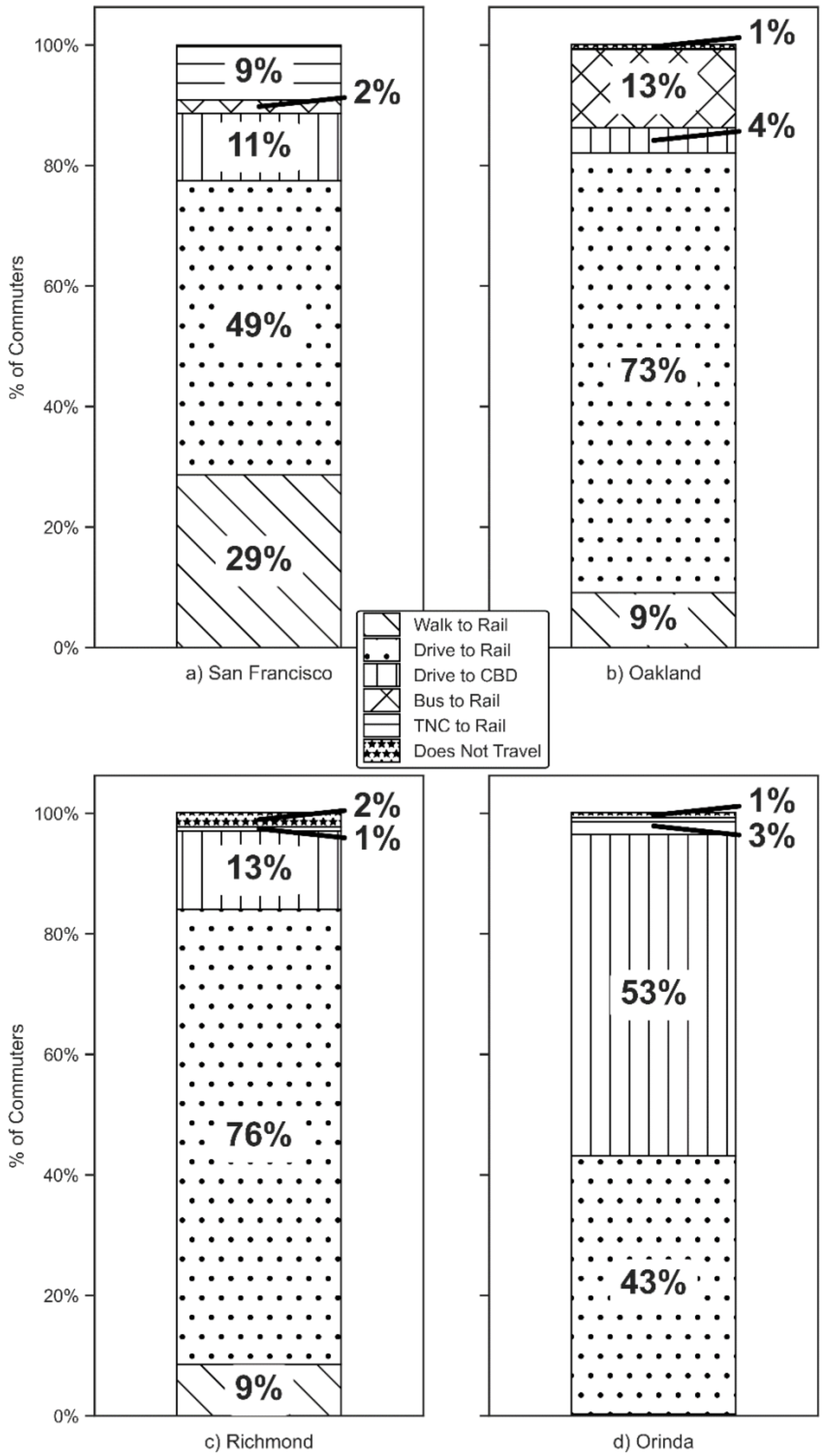


Figure 6. Modal Split for Four Bay Area Communities in the Baseline Case

3.1.3 Modal Split of Commuters Who Lack Access to Cars

Commuters who do not own personal cars commute by whichever non-driving modes are most prevalent in their community. In San Francisco, 63 percent of commuters who do not own cars walk, largely due to the walkability of the area surrounding the rail station. In Oakland, which has good feeder bus service in the area near the rail station, 76 percent of commuters without cars ride the bus. Despite Orinda's lower walkability and sparse bus transit, and because of the high value of time, 92 percent of those without cars use unsubsidized TNC to access rail. Richmond is an outlier in this case, because it has a medium level of walkability and medium level of bus transit near the rail station but also the lowest value of time among the communities. None of these characteristics provide Richmond commuters without cars a viable option, so most walk to rail (76 percent). A small group of higher-income Richmond commuters without cars use unsubsidized TNC (22 percent).

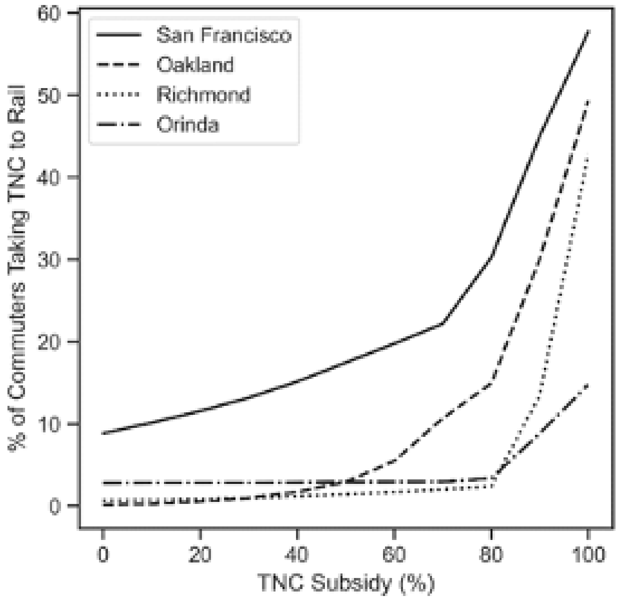
3.2 Common Outcomes

The communities exhibit similar responses to several different policy combinations. The shared outcomes from testing TNC subsidies alone are described first, followed by shared outcomes from pairing TNC subsidies with increases in rail parking fees. The final subsection discusses the potential for using cross-subsidies in the communities.

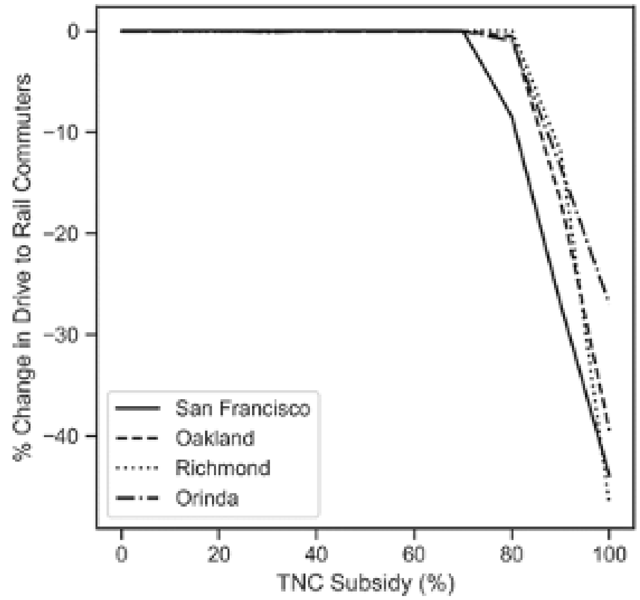
3.2.1 Outcomes of TNC Subsidies Alone

Commuters who drove to the station in the baseline can be persuaded to leave their cars at home and take TNC to rail if the per-trip TNC fare is heavily subsidized by a minimum of 70–80 percent. Figure 7a shows that all four communities exhibit an increase in commuters taking TNC to and from rail. Notice an "elbow" in each curve at the aforementioned subsidy levels. This point is at 70 percent subsidy for San Francisco and Oakland, and 80 percent for Richmond and Orinda. The elbow point is tied to the subsidization level at which commuters who previously drove to rail shift to TNC, as presented in Figure 7b. In the lower subsidization levels before the elbow point, San Francisco and Oakland have a more gradual increase in TNC use, while Richmond and Orinda show an abrupt increase at the elbow. The reason for these responses to TNC subsidization is that San Francisco and Oakland have a proportion of commuters who previously rode the bus or walked to rail. These commuters start shifting to TNC at low subsidy levels. A greater subsidy level is needed before commuters who drive to rail shift to TNC. There are limited alternatives to driving in Richmond and Orinda, so that TNC is competitive only at higher subsidy levels. This creates the sharp jump in TNC use when subsidies are above 80 percent of the original fare.

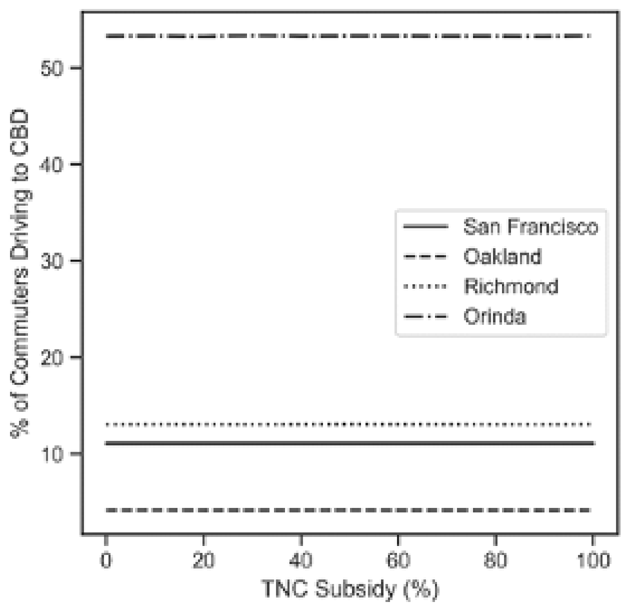
The number of commuters who choose to drive to rail decreases between 27 and 47 percent across the four communities. Not surprisingly, the maximum mode shift occurs when TNC is fully subsidized (i.e., free).



a. **TNC to rail commuters**



b. **Drive to rail commuters**



c. **Drive to CBD Commuters**

Figure 7. Percent of All Commuters Taking TNC to Rail, Driving to Rail, and Driving to CBD under Different TNC Subsidy Levels

Increasing the TNC subsidy, even to 100 percent, has no effect on commuters who drive directly to the CBD, no matter the community (see Figure 7c). These commuters have a higher value of time than do others, have access to a car, and live closer to the highway entrance than to the rail station. Even though highway commuters experience time-varying congestion, highway entrance tolls, and the steep cost of downtown parking, for high-value-of-time commuters these expenses are less burdensome than riding in a TNC and on a train.

3.2.2 Outcomes from Pairing TNC Subsidies with Higher Rail Parking Fees

Although commuters who drive directly to work are unresponsive to TNC subsidies, subsidization policies do work in shifting people who drive to the rail station. Raising the fees for rail parking can improve the efficacy of TNC subsidization. Increasing these fees can also increase the shift in commuters who previously drove to rail. Figure 8 shows the decrease in commuters who drive to rail when rail parking fees are increased at two fixed TNC subsidy levels, a 0 percent subsidy and a 100 percent subsidy. As rail parking fees increase, commuters who drive to rail change modes, even at a zero TNC subsidy level. When paired with a high (100 percent) TNC subsidy level, (e.g., Figure 8b), increased rail parking fees are effective at disincentivizing commuters from using their cars.

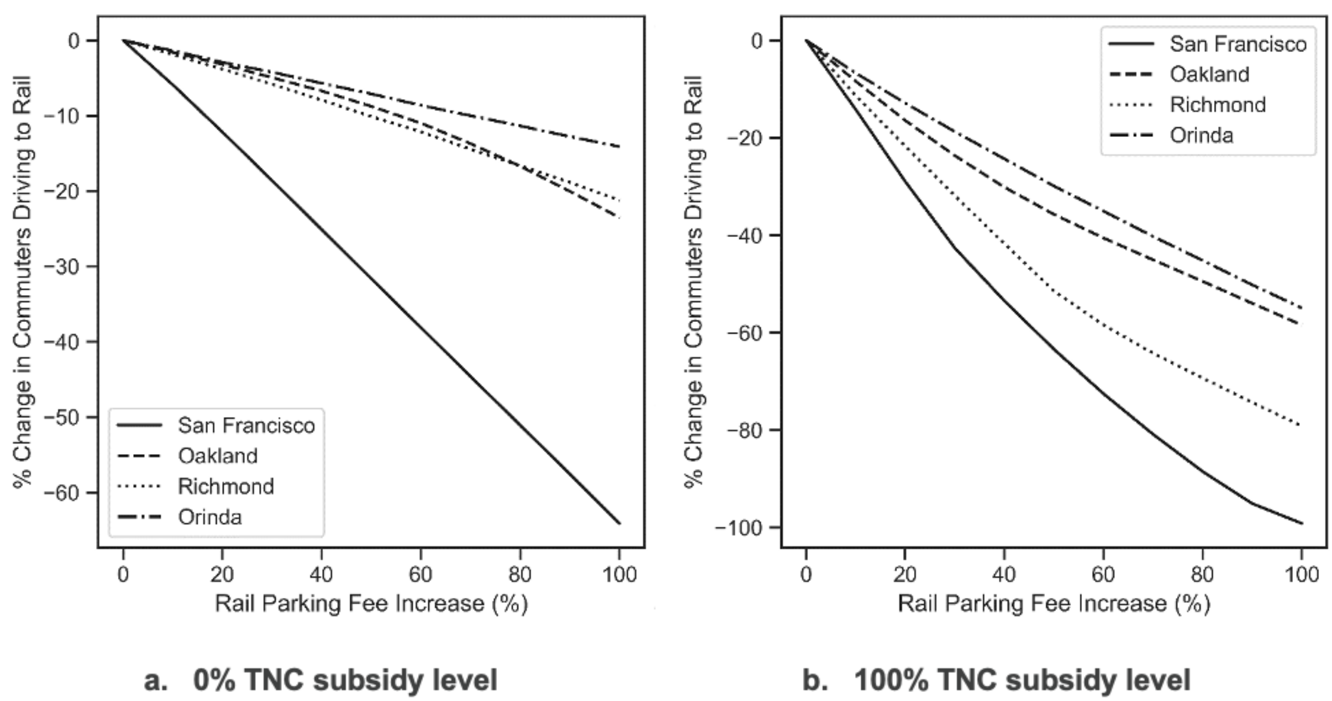


Figure 8. Percent Change to Number of Commuters Driving to Rail under Different Rail Parking Fee Levels

Increasing rail parking fees in tandem with TNC subsidies is not without potential negative effects. Higher fees induce some commuters who previously drove to rail to shift to driving directly to the CBD. This shift would potentially increase highway traffic and reduce rail ridership. The effect cannot be mitigated by providing additional TNC subsidy. Even full subsidization has no effect on commuters who drive to the CBD, including those who shifted from driving to rail.

Figure 9 shows that raising rail parking fees without subsidizing TNC leads to precipitous increases in commuters who drive directly to the CBD. This is most apparent in San Francisco because it is the community closest to the CBD (approximately 8 kilometers) and highway drivers are not tolled. This makes driving to CBD the lower cost option for many San Francisco commuters. Slight increases in rail parking fees more than double the proportion of San Francisco commuters who drive to the CBD. Oakland commuters respond similarly, as their proximity to the CBD (approximately 12.5 kilometers by highway) outweighs the cost of tolls. Richmond and Orinda commuters also shift to driving to CBD after rail parking fees are increased. However, due to their longer driving distance and the cost of tolls, the rate of increase for Richmond and Orinda drivers is much more gradual and has a lower maximum mode shift than those in San Francisco and Oakland. Richmond and Orinda experience commuters who previously drove to rail shifting to driving directly to the CBD at a rate of a 1.5 percent and 1.1 percent increase per 10 percent fee increase, respectively. San Francisco and Oakland experience a rate of 4 percent and 13 percent increase per 10 percent fee increase, respectively. Doubling the rail parking fee in Richmond and Orinda results in increases in the number of commuters who drive directly to the CBD by 15 percent and 11 percent, respectively.

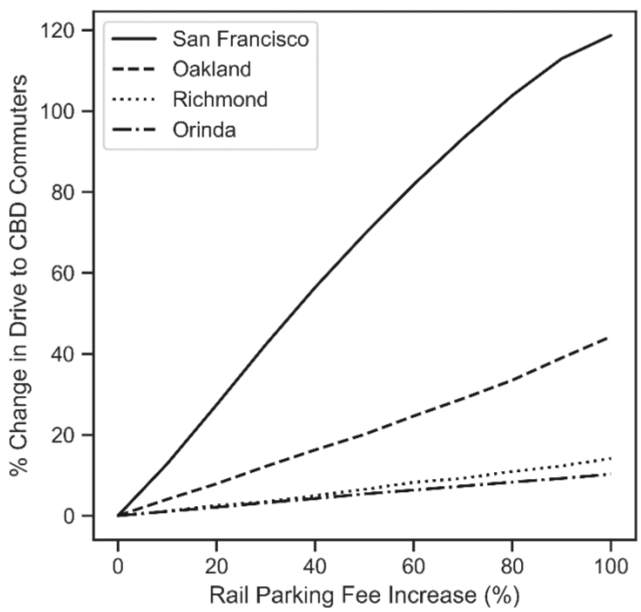


Figure 9. Percent Change to Number of Commuters Driving Directly to the CBD for Different Rail Parking Fee Levels at Any TNC Subsidy Level

Clearly, the negative effect of raising rail parking fees should be considered when determining the subsidization policy for improving rail access via TNC.

3.2.3 Cross-Subsidization Outcomes

The subsidization tests show that policy combinations exist that allow all four Bay Area communities to use extra revenue (from increased rail parking fees) to cover some or all TNC subsidy costs.

presents the total cost that an administrator would pay to subsidize TNC feeder service for their community, in $1000s per day. The darker areas indicate surplus revenue after using the extra rail parking revenue to cover TNC feeder subsidies, and the lighter areas indicate policy combinations where the extra rail parking revenue falls short of fully covering all TNC costs, such that additional funding is required. The contour lines indicate policies with identical extra revenue outcomes. The “$0K” contour line marks policies where the cost of a TNC subsidy is fully covered by extra rail parking revenue with little leftover.

The policy combinations that result in nearly even cross subsidies vary between communities. San Francisco has nearly full coverage with low TNC subsidies and high increases to rail parking fees. This is due to the high number of commuters in San Francisco, so providing a large subsidy to all of them without additional revenue would be extremely costly. Oakland can cover all the costs of providing a 70 percent TNC subsidy with between a 50 and 100 percent increase to rail parking fees. Richmond and Orinda exhibit similar potential cross-subsidy combinations, primarily with using low parking fee increases to cover 70 to 80 percent TNC subsidies.

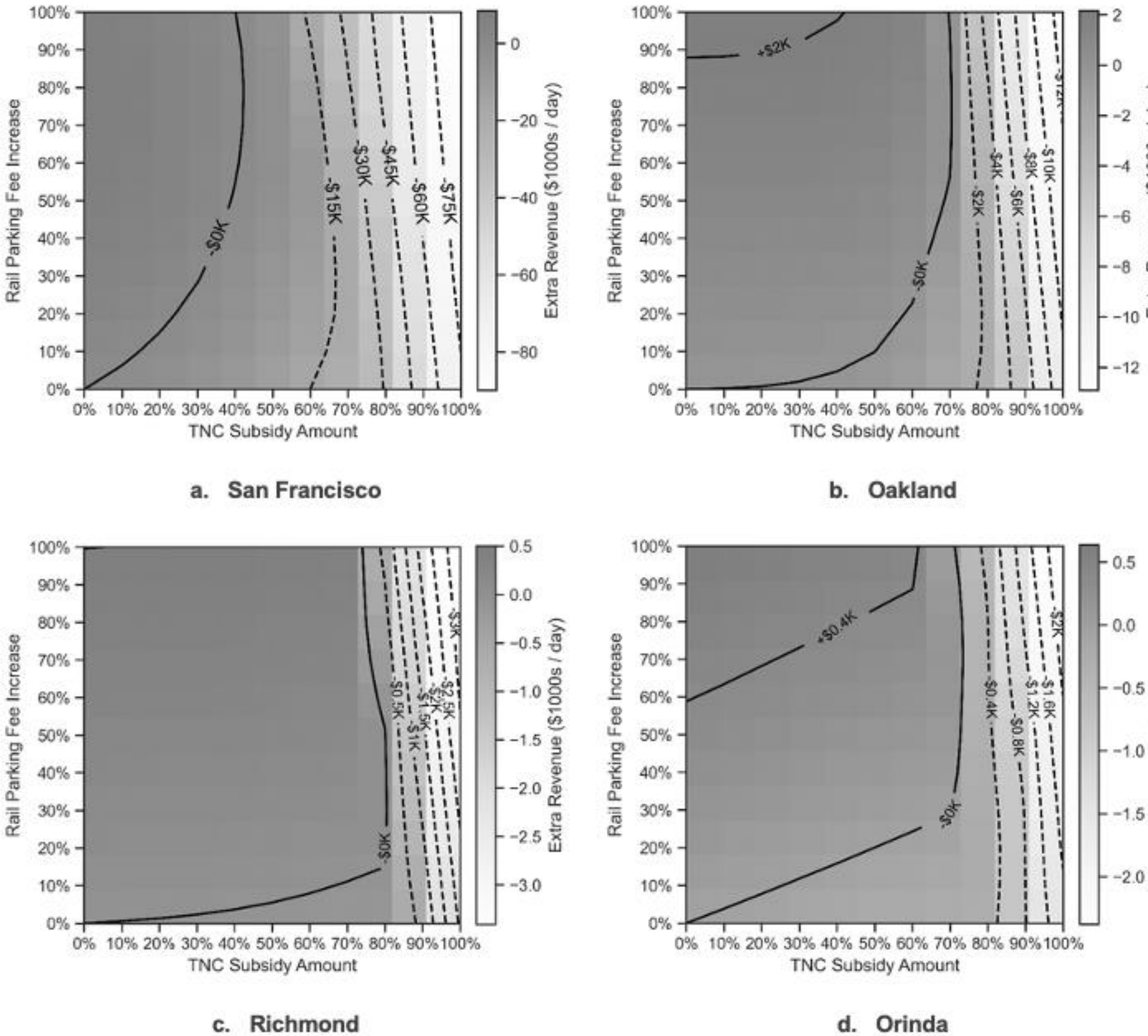


Figure 10. Extra Revenue (in $1000s/day) for Different Policy Combinations

3.3 San Francisco and Oakland Policy Outcomes

San Francisco and Oakland are distinct as communities because rail can readily be accessed on foot or via feeder bus. San Francisco is densely populated and highly walkable, with the largest baseline proportion of commuters who walk to rail (29 percent). Oakland has numerous bus lines that connect to its rail stations. Oakland thus has the highest baseline proportion of commuters who take bus to rail (13 percent). During the subsidization tests, it became apparent that commuters who take these more sustainable modes are among the first commuters to shift to TNC and will do so at a subsidization level far below that of commuters who drive to rail. The proportion of commuters walking in San Francisco or riding the bus in Oakland at different TNC subsidization levels are provided in

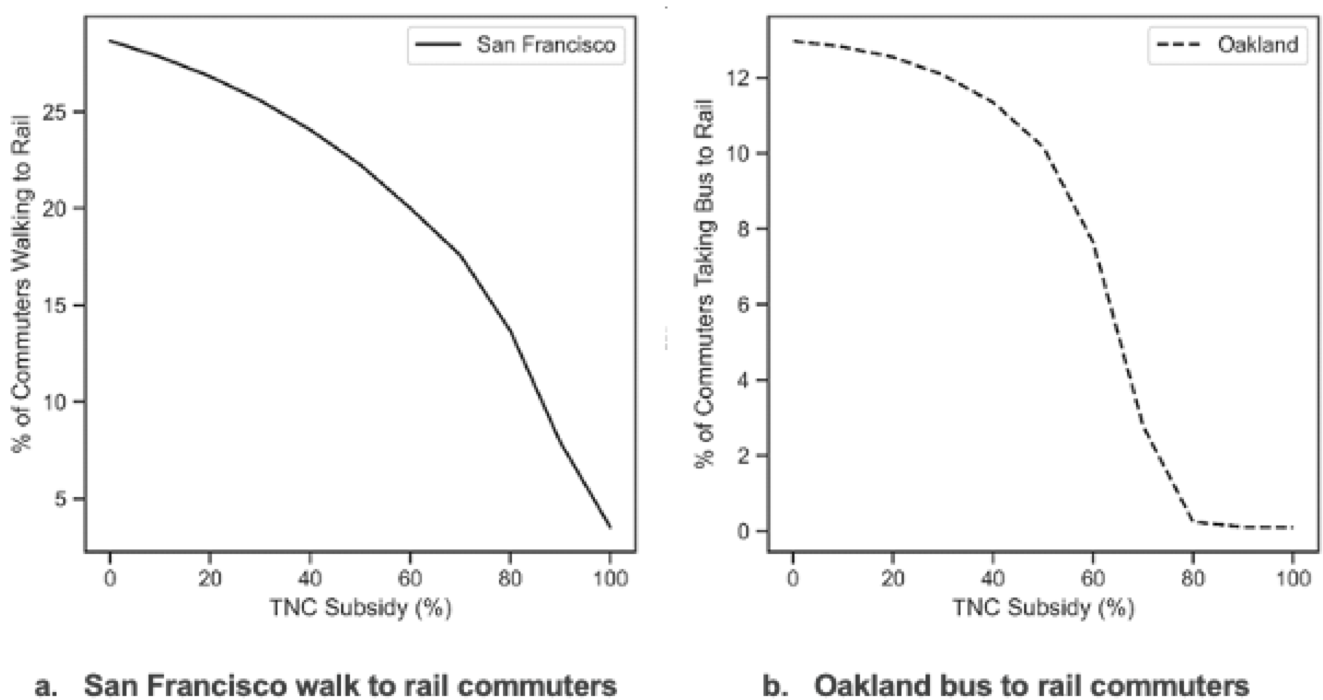
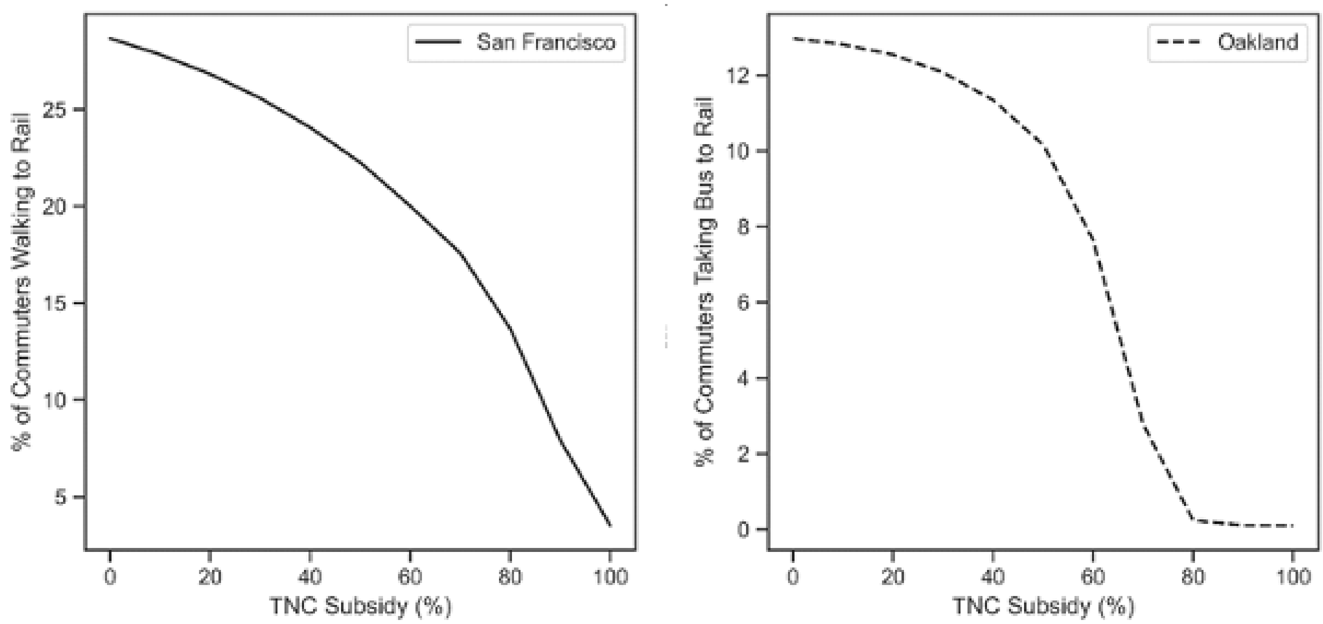


Figure 11.

When the TNC fare is subsidized by 40 percent, Oakland commuters who previously took the bus to rail shift to using TNC en masse. Nearly all former bus commuters use TNC when their fares are subsidized by 80 percent or more. San Francisco commuters who walk to rail shift to TNC less dramatically, but there is still an "elbow" point at the 50 percent subsidy level. Nearly all San Francisco commuters who walked in the baseline, shift to TNC when their fare is subsidized by 90 percent. These elbow points occur at subsidy levels much lower than the aforementioned points for the commuters who drive to rail (see Figure 7b in Section 3.2.1).

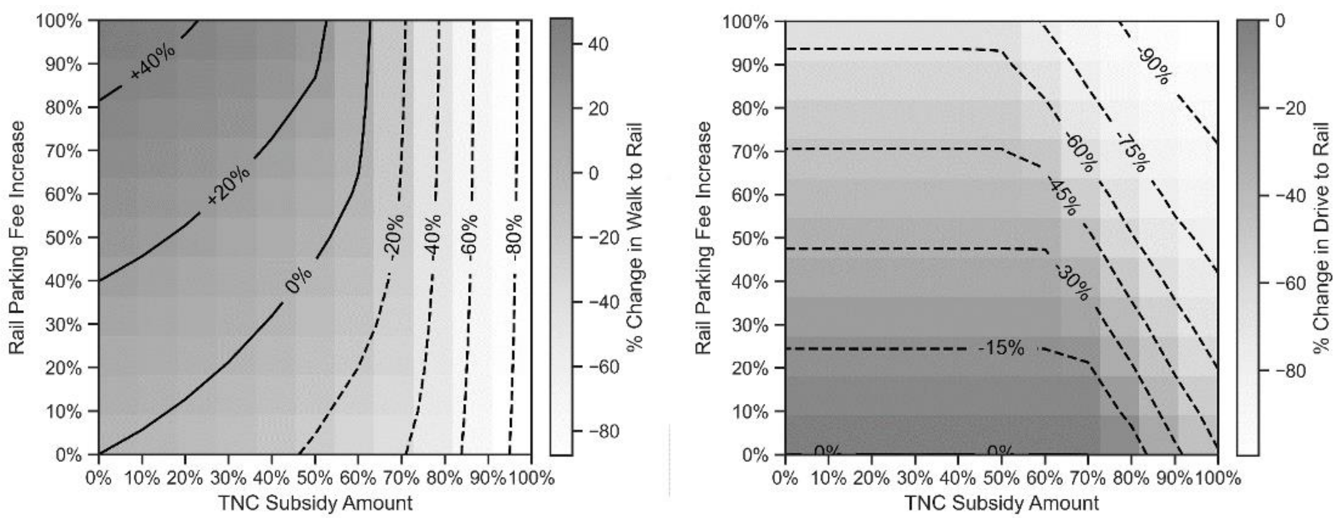


a. **San Francisco walk to rail commuters**

b. **Oakland bus to rail commuters**

Figure 11. Percent of Commuters Taking Alternative Feeder Modes under Different TNC Subsidy Levels in San Francisco and Oakland

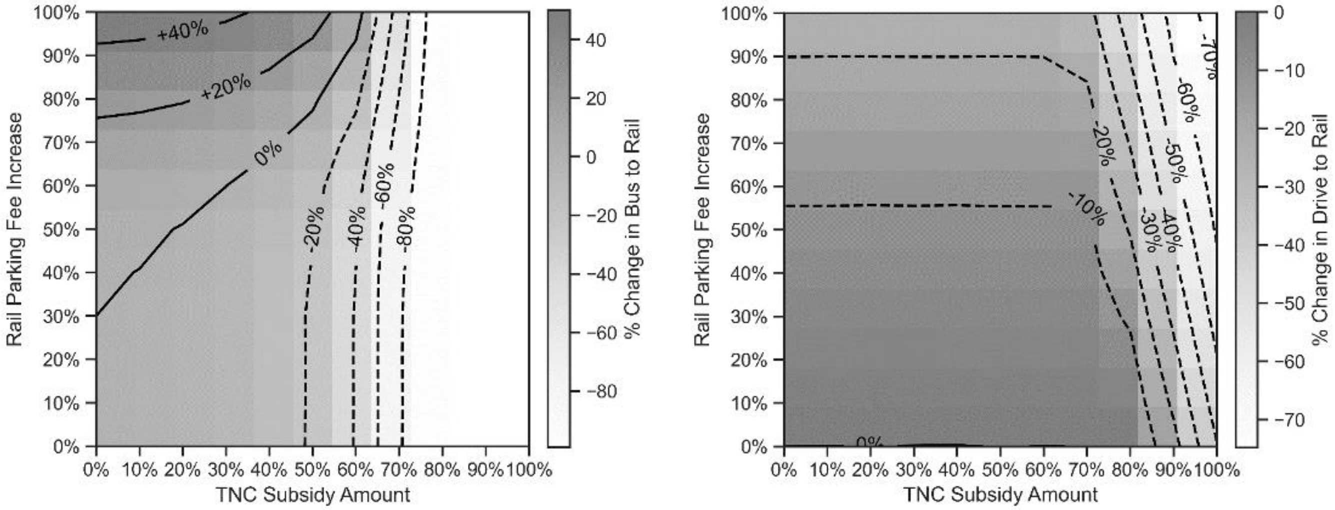
As mentioned, increasing rail parking fees can successfully lower the TNC subsidy threshold needed to shift drive-to-rail commuters. Keeping TNC subsidies low also maintains the majority of commuters who walk or take the bus. The heatmaps in



a. **Walk to rail mode share**

b. **Drive to rail mode share**

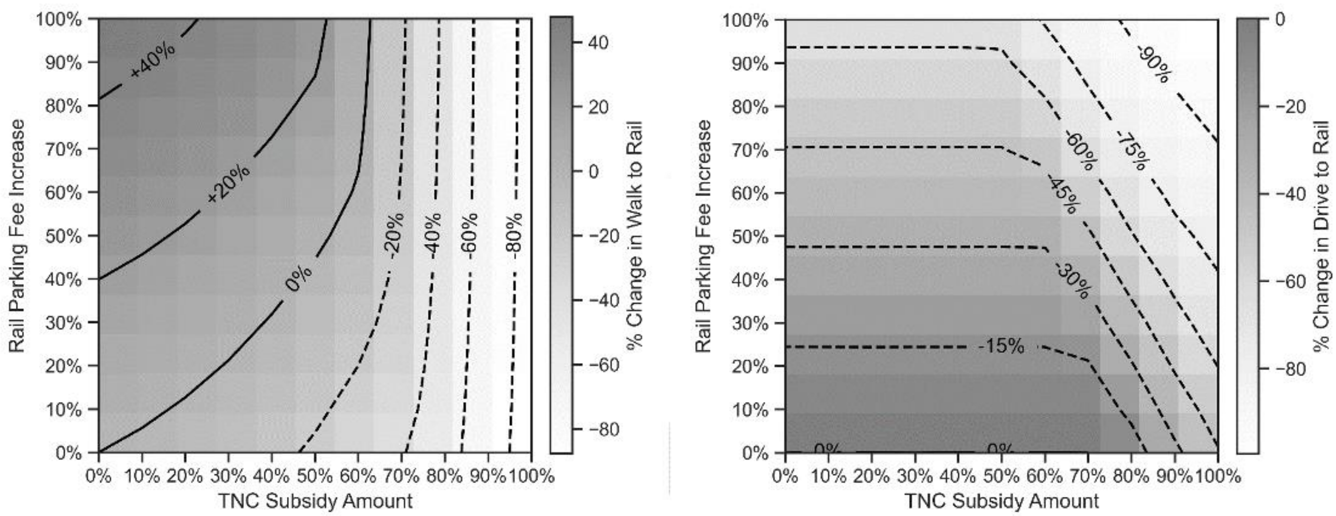
Figure 12a and



a. **Bus to rail mode share**

b. **Drive to rail mode share**

Figure 13a present the percent change to the walk commuters in San Francisco and the bus commuters in Oakland, respectively, under different policy combinations. The heatmaps in



a. **Walk to rail mode share**

b. **Drive to rail mode share**

Figure 12b and

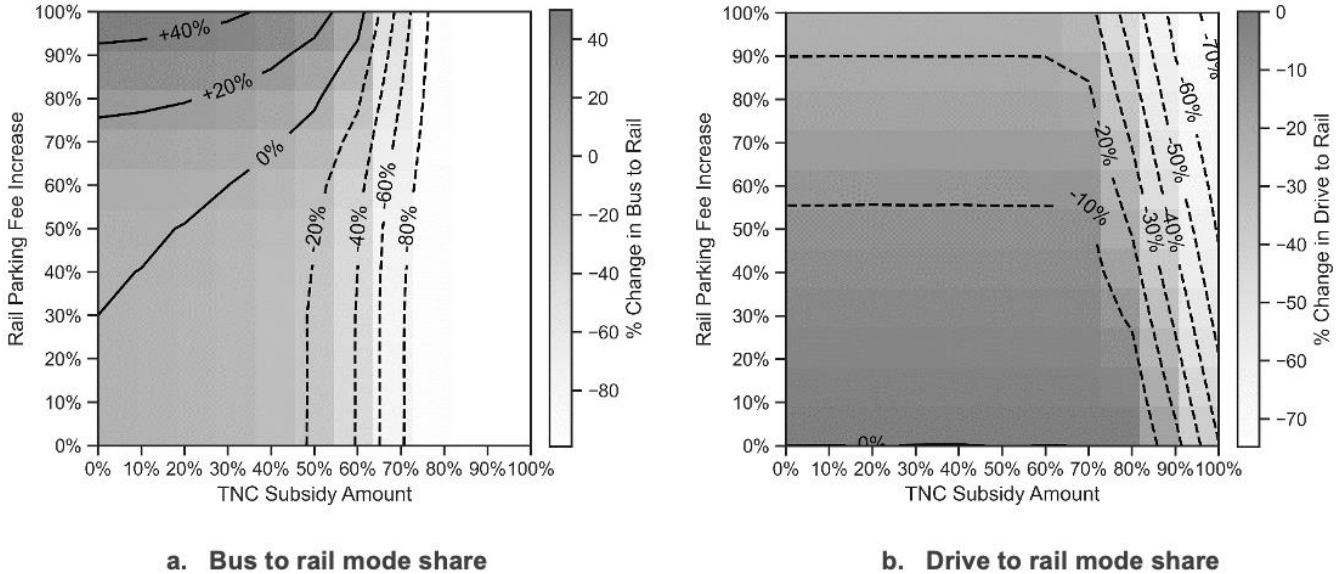
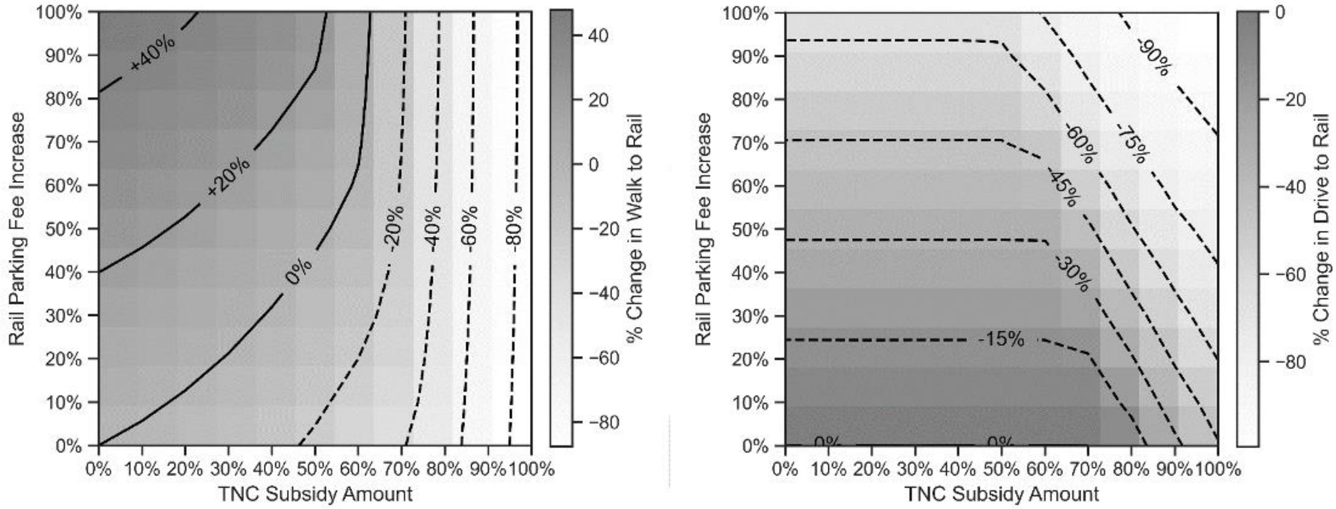


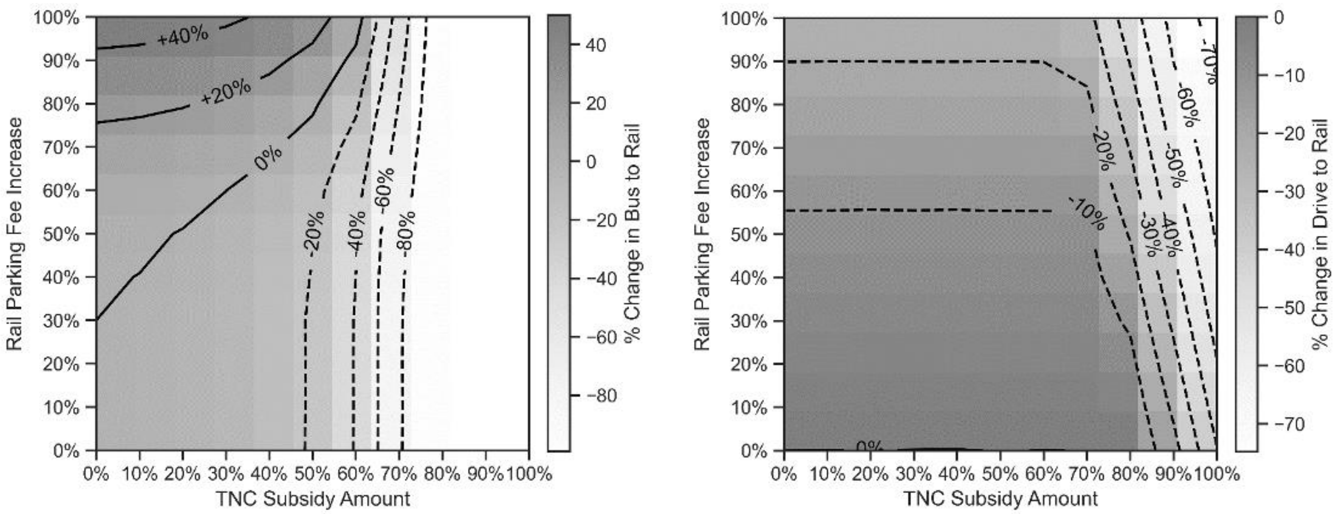
Figure 13b show the effect of the same policy combinations on the drive-to-rail commuters in both communities. Contour lines in Figures 12 and 13 indicate policies that induce the same percent change. Shifting as few walk or bus commuters as possible is a constraint on policy selection, but some combinations of TNC subsidy and fee increases that minimally affect that type of commuter can still be reasonably effective at shifting commuters who drive to rail to TNC. For example, in San Francisco, a 60 percent TNC subsidy coupled with a 60 percent fee increase decreases walk-to-rail commuters by only 1.3 percent while decreasing the number of drive-to-rail commuters by 40 percent. Oakland commuters respond similarly; a 40 percent TNC subsidy paired with a 70 percent fee increase leads to a 2 percent increase in bus commuters, but decreases the number of drive-to-rail commuters by 14 percent.



a. **Walk to rail mode share**

b. **Drive to rail mode share**

Figure 12. Change in Mode Share for San Francisco under Different Policy Combinations



a. **Bus to rail mode share**

b. **Drive to rail mode share**

Figure 13. Change in Mode Share for Oakland under Different Policy Combinations

However, increasing the rail parking fees in the manner described does lead to an increase in commuters shifting to drive directly to the CBD, especially in San Francisco. The proposed 60 percent fee increase in San Francisco results in a 90 percent increase in commuters who drive to the CBD. The 70 percent fee increase in Oakland would increase the number of drive-to-CBD commuters by 24 percent. Though the increase in commuters driving to the CBD may be small in number, additional cars on the regional highways is a negative result, and the policies selected for San Francisco and Oakland should aim to avoid contributing to regional congestion. Therefore, the best policy for these communities is to avoid raising rail parking fees so as not to induce commuters who drive to rail to shift modes.

Removing the rail parking fee increases as a policy lever limits the efficacy of subsidization-only policies in San Francisco and Oakland. Further complicating policy selection is the fact that the policy selected must ensure that TNC does not compete with bus and walking modes. These constraints limit the potential for subsidized TNC feeder service in San Francisco and Oakland, particularly one provided to all commuters. Subsidizing TNC universally in these communities could cause more harm than good.

A more viable solution for San Francisco and Oakland might be to provide subsidized TNC service to specifically low-income commuters. In the baseline scenario, low-income commuters mainly walked long distances to rail or opted not to travel at all due to high commute costs. To provide TNC service to the majority of low-income commuters, a subsidy level of 80 percent or more is necessary. Providing low-income commuters with timely, low-cost access to rail has the potential to increase their average daily net benefit by up to 10 percent in San Francisco and 14 percent in Oakland (see Figure 14) and decrease the number who could not afford to travel in the baseline by 8 percent in San Francisco and 13 percent in Oakland.

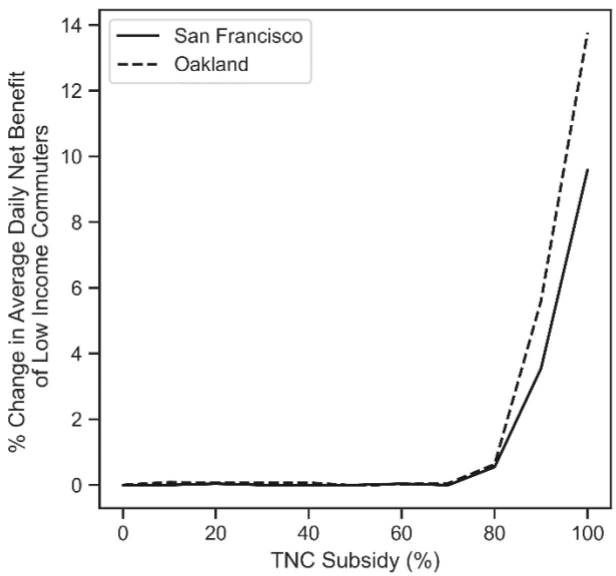
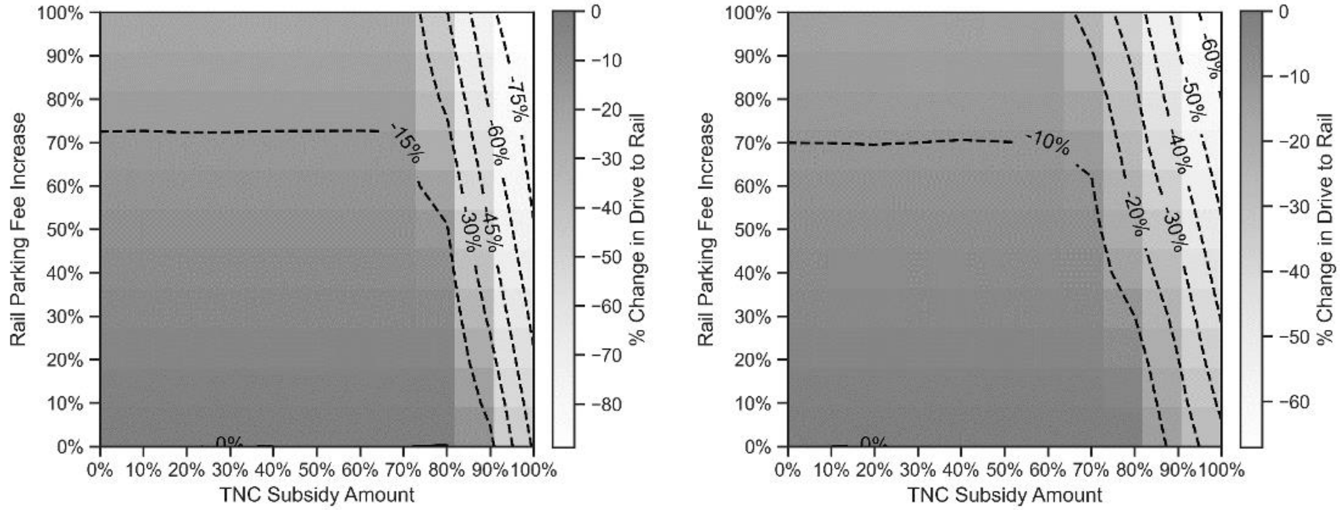


Figure 14. Percent Change to Average Daily Net Benefit for Low-Income Commuters under Different TNC Subsidization Levels in San Francisco and Oakland

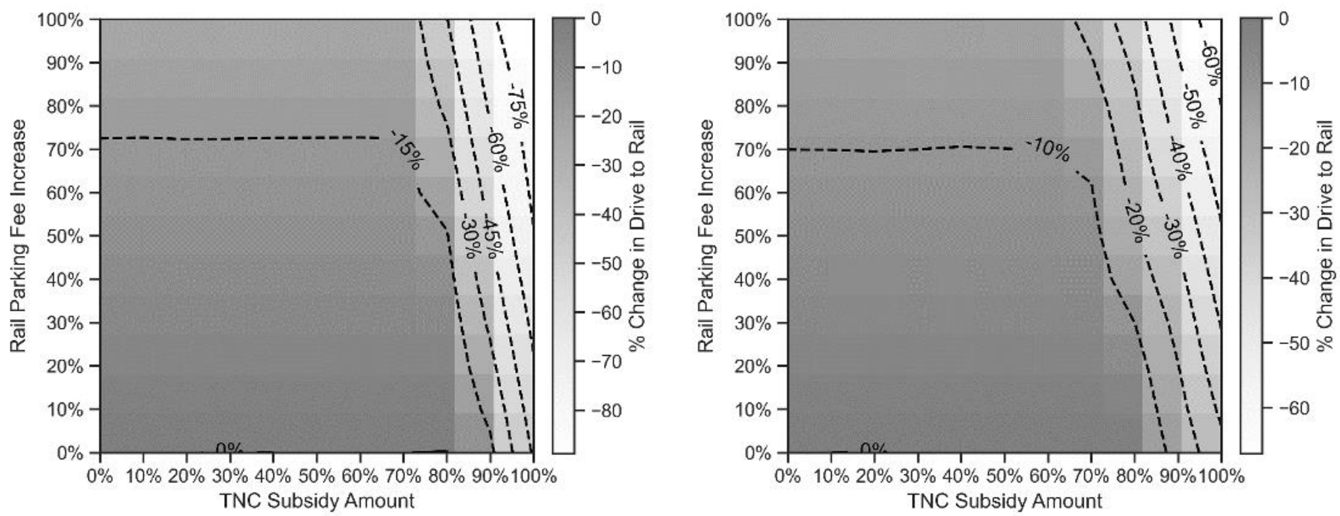
3.4 Richmond and Orinda Policy Outcomes

Although commuters in Richmond and Orinda have different average income levels, the communities share many characteristics: low population density, high vehicle ownership rate, and limited feeder bus service near rail stations. The subsidization tests show that these characteristics make Richmond and Orinda suitable for using subsidized TNCs to shift commuters from driving to the rail station to taking TNC. As



a. Richmond **b. Orinda**

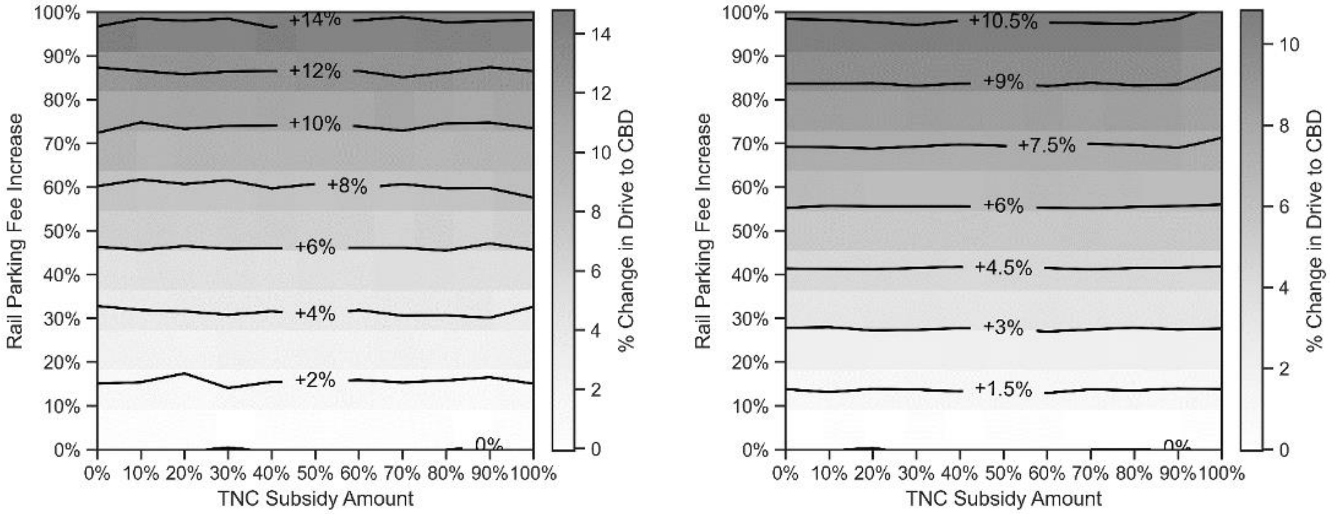
Figure 15 shows, using only a 90 percent TNC subsidy leads to a 12 percent and 13 percent decrease in drive-to-rail commuters in Richmond and Orinda, respectively, and fully subsidized TNC shifts 47 percent and 27 percent of commuters away from driving to rail, respectively. Increasing rail parking fees can increase the shift away from driving to rail for lower TNC subsidy levels.



a. Richmond **b. Orinda**

Figure 15. Drive to Rail Mode Shift under Different Policy Combinations in Richmond and Orinda

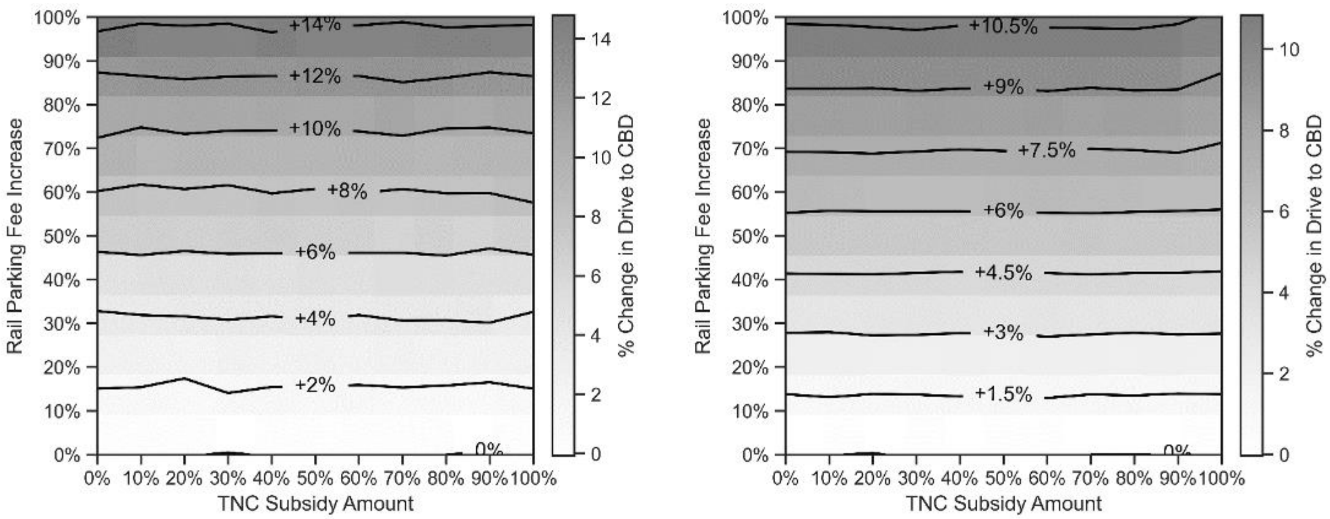
As shown in



a. Richmond

b. Orinda

Figure 16, increasing rail parking fees does lead a portion of Richmond and Orinda commuters shifting from driving to rail to driving directly to the CBD. However, this shift increases at a much lower rate than in the other communities tested. Richmond and Orinda experience a lower increase in commuters who drive to CBD because both communities are far from the CBD, so commuters who drive on the highway experience traffic congestion for longer than commuters from closer communities. Therefore, the cost of driving on the highway from Richmond and Orinda is much closer to rail transit levels.



a. Richmond

b. Orinda

Figure 16. Drive to CBD Mode Shift under Different Policy Combinations in Richmond and Orinda

In high TNC subsidy scenarios, per 10 percent fee increase, commuters in Richmond and Orinda shift to driving to the CBD at a rate of 50 percent and 63 percent lower than the rate at which they shift to taking TNC to rail, respectively. Depending on the community's tolerance for shifting a small number of commuters to the highway, this might be a worthwhile trade-off if the larger number of commuters shifting to use TNC is viewed as more beneficial.

To capitalize on the benefits of reducing the number of commuters who drive to rail, Richmond and Orinda should subsidize TNC service as much as possible. Without increasing rail parking fees, a fully subsidized TNC service will decrease commuters who drive to rail by 47 percent in Richmond and by 27 percent in Orinda. If the communities tolerate a 5 percent increase in commuters using the highway, Richmond can use a policy combination that increases rail parking fees by 20 percent and Orinda by 30 percent. Parking fees set at these increased levels result in a 58 percent and 41 percent decrease in drive-to-rail commuters in Richmond and Orinda, respectively. The total per-day cost to fully subsidize TNC (including costs offset by the extra rail parking revenue) would be approximately $2.5 thousand per day for 220 commuters in Richmond, and approximately $1.7 thousand per day for 170 commuters in Orinda.

4. Discussion and Conclusions

We first provide a menu of strategies for implementing TNC subsidies and discuss their feasibility. We then conclude with a recapitulation of the main findings from the TNC subsidization tests and present potential areas for future research.

4.1 Subsidization Strategies

Four strategies to subsidize TNC feeder service are presented in the following subsections: use of parking fees at rail stations as a cross subsidy (Section 4.1.1); building partnerships with TNCs to distribute subsidies in a targeted fashion (Section 4.1.2); leasing excess rail parking and converting it to revenue-generating transit-oriented developments (Section 4.1.3); and reallocating existing resources from low-ridership bus routes (Section 4.1.4).

4.1.1 Cross Subsidization

As mentioned in Section 3.2.3, using revenue from higher rail parking fees as a cross subsidy for TNC feeder service could be a viable strategy, although it is dependent on the features of the community and the policy combination selected. Implementing TNC subsidies without pairing them with a higher rail parking fee could result in not enough extra revenue to sufficiently cover the subsidization costs. Therefore, only a few TNC subsidy-rail parking fee combinations are feasible as cost-neutral, cross-subsidy options.

Due to additional constraints, no feasible cross-subsidy policy combination exists in some communities. Under these circumstances, a different subsidization strategy would be necessary. For example, in Oakland, despite several policy combinations ending up cost-neutral (see

b), none of them are feasible because of the additional constraints on Oakland: the TNC subsidy should not be increased to a level that decreases bus ridership; and the rail parking fee should not be increased to a level that increases the number of commuters driving to the CBD. The constraints on the Oakland scenario unveils the need for an equity-focused subsidization policy. However, the tested policy (a full TNC subsidy for low-income commuters) results in a daily cost that would not be covered by rail parking fees. Thus, a different subsidization strategy is necessary to implement this policy.

If cross subsidization is used to subsidize TNC, administrators must ensure that the subsidies and fee increases are applied equitably. In our model, we assume commuters of different income levels are distributed evenly across the community. However, this is rarely the case in the real world. Cross subsidies need to be applied with some degree of nuance to ensure that they are not regressive (*17*). It is possible that many commuters who drive to rail and pay the increased parking fee earn lower incomes but continue to drive to rail after TNC is subsidized due to their proximity to the station. The group who predominantly receives the TNC subsidies could also end up being high-income commuters who live farther away. Despite the TNC commuters bearing a greater commuting cost, the cost makes up a smaller percentage of their overall income because of their higher income. Therefore, an increase in rail parking fees can disproportionately impact those who drive to rail. The cross-subsidization policy must be catered to local conditions in the communities where subsidies are applied.

4.1.2 Partnering with TNCs to Subsidize Low-Income Commuters

In some communities, subsidies for a TNC feeder could cause reductions in bus ridership or active feeder modes, like walking. In these communities, a more sustainable policy to improve feeder service should be used, such as one focusing on providing TNC subsidies to specific groups of commuters in need, such as those with low incomes. One way to distribute subsidies under this policy is to partner TNCs with transit agencies to determine where subsidies should go. However, this option would result in a considerable amount of administrative overhead for checking commuter eligibility and record keeping.

A second option is for TNCs to partner with social service agencies and community-oriented nonprofit organizations for subsidy distribution. These organizations have existing infrastructure to administer such programs as well as the contact lists and records of currently eligible individuals. Transit agencies often work with these organizations to distribute fare vouchers to low-income riders. Distributing TNC subsidies pairs nicely with existing programs, because they can ensure low-income commuters can access transit in the first place. Additionally, many social service agencies already have existing transportation assistance programs, although they rarely incorporate TNCs (*18*, *19*). As a local example, Alameda County Social Services provides transportation assistance for program participants who are in school, working, or in a training program by paying for transit passes or assisting individuals with cars by providing a mileage reimbursement (*20*). Instead of (or in addition to) the latter option, Alameda County could partner with a TNC to distribute ride vouchers to low-income commuters so that they no longer need to drive to work.

4.1.3 Converting Excess Rail Station Parking to Transit-Oriented Developments

Commuters shift from driving to rail under some of the policy combinations tested, particularly those with high TNC subsidies and some increase in rail parking fees. Many rail stations already supply much more parking than is demanded (*21*). Only one of the BART rail stations in a community tested (Oakland's Lake Merritt station) has limited capacity during the day. The other three stations have excess capacity at all times (*22*). The existing parking surplus coupled with a shift from driving to rail induced by TNC subsidization could lead to a dramatic decrease in the rail parking necessary. Unused rail parking space is highly valued due to its proximity to rail transit. Revenue can be generated by leasing underutilized parking areas and converting them into more productive land uses, such as retail or residential spaces as part of a transit-oriented development (*23*). These revenue streams can be leveraged toward various rail-supporting projects, including subsidizing TNCs to provide improved feeder service for commuters that do not live in the new developments (*24*).

Transit-oriented developments bring additional benefits to rail stations in their proximity. Naturally, removing parking decreases vehicle use, but having a portion of the developments converted into housing can improve rail ridership as more people can walk to rail (*25*). Dedicating a portion of new developments to below-market-rate housing can support low-income commuters via lower housing and commute costs (*26*). BART has several upcoming projects planning to do just this (*27*).

4.1.4 Reallocating Resources from Low-Ridership Bus Lines

Each community tested has bus service that connects to its rail station. However, there is a large variance in the level of service provided across communities. San Francisco and Oakland have frequent bus service that acts as a feeder for rail for some commuters. The buses in Richmond, on the other hand, mostly provide local, many-to-many service for the area surrounding the rail station. Orinda has a dedicated feeder bus line for its rail station, but it is low frequency and has limited service hours. The route's low frequency makes it an inefficient feeder option for those who need it, resulting in low daily ridership—the Richmond route carries 275 passengers per day, and the Orinda route carries 229 passengers per day (*28*, *29*). Low daily ridership leads to a low fare-box return, requiring the transit agencies to pay costly subsidies per passenger. Both routes cost more than $20 per passenger trip (*30*, *31*). The subsidy per passenger for running these routes is nearly three times that of a fully subsidized one-way TNC fare.

Reallocating resources from low-ridership, low-frequency bus lines to subsidize TNC feeder service could be a viable strategy. On a per-trip basis, replacing low-ridership feeder bus lines with subsidized TNC can be more cost effective for transit agencies and provide more efficient service to the commuters who rely on them, especially in communities with lower population densities (*32*). Existing bus routes that serve trunk lines and other parts of a community should retain full resources, but because low-ridership feeder bus routes are primarily used for accessing rail stations, replacing costly feeder routes with subsidized TNC service will minimally impact the system-wide ridership.

4.2 Key Takeaways

We developed idealized models to represent Bay Area communities and generated synthetic commuter populations to parametrically test different subsidization policies for TNC feeder service. The main findings from the tests are as follows:

- Commuters who drive to rail can be persuaded to leave their cars at home and use TNC if the service is subsidized by 70–80 percent and rail parking fees are increased by a couple of dollars.
- Increasing rail parking fees induces high-income commuters to shift from driving to rail to driving directly to the CBD. This negative effect is more pronounced in communities located closer to the CBD.
- Commuters who currently drive to the CBD will not shift to taking rail transit, even if a TNC feeder service is fully subsidized. This can be attributed primarily to proximity (they live closer to the highway entrance) and to a high value of time (even with highway congestion, driving to CBD is faster, and the tolls and downtown parking are a fair trade-off for earning their higher daily net benefit).

- There is no one-size-fits-all TNC subsidization policy for all communities. The policies need to be tailored to local conditions, such as the income level of commuters, population density, availability of alternative feeder modes, distance from the CBD, and vehicle ownership rate.
- In communities with high-frequency bus service available as a feeder (such as Oakland), TNC subsidization will directly compete with bus service if the subsidy is too high. A more nuanced, equity-based approach may work better at targeting groups and individuals in need, rather than subsidizing TNC in all neighborhoods, including those sufficiently served by bus transit.
- In densely populated, walkable communities (such as San Francisco), subsidizing TNC may induce use of those vehicles by commuters who previously walked to rail. While those who walk a lengthy distance to reach rail transit as a lower-cost alternative largely benefit from subsidized TNC, individuals who could comfortably walk a short distance to rail most likely do not need a TNC feeder. Using an equity-based strategy to provide subsidized TNC for commuters who are unable to walk to their rail station can improve efficiency for those who need it without unnecessarily inducing demand for car-based commute modes.
- For communities with lower population densities, limited bus service, and high vehicle ownership rates (such as Richmond and Orinda), subsidizing TNCs as a feeder service should be a beneficially impactful process. However, care should be taken when disincentivizing commuters who previously drove to rail because these commuters might shift from transit altogether. Using alternative funding methods other than rail parking revenue for cross subsidization could mitigate this problem. For communities with bus service that is not solely used as a feeder for rail (such as Richmond), turning excess rail parking into transit-oriented developments with retail or housing could be one way of garnering funds for TNC subsidies. For communities with existing but infrequent feeder bus service (such as Orinda), funding for the existing feeder service could be reallocated to cover the subsidies for TNC feeder.

4.3 Future Research

Exploring the potential for TNCs to serve as a feeder service for rail transit unveils multiple avenues for future research. First and foremost, our models can be expanded to express additional nuances of real-world communities. Introducing non-homogeneity in the form of different levels of bus service and TNC access within an area and grouping similar commuters into neighborhoods can help determine how different groups are affected by policies. This could result in more equitable subsidization or cross-subsidy policies. Additionally, modeling TNC operations, such as pooling, could help identify emergent effects that are otherwise not visible in our single-rider model. These additions may also be more realistic because shared origins and destinations of a rail station make TNC feeder service a good candidate for pooling. Finally, testing other operational changes, such as the use of shared commuter meeting points in low-density areas, could help lower TNC subsidization costs and improve commute efficiency by aggregating demand and making use of straight-line routing.

Yet even now, the research can serve as the basis for real-world application. A pilot study could be administered to see how different levels of TNC subsidy impact commuters in real-world communities. These can be selected based on demographic characteristics, proximity to the CBD, and quality of existing feeder modes. Commuters can enroll in the study and will then be randomly assigned a TNC subsidy level. Participating commuters can log the modes they take every day for their commute in an app developed for the pilot. Using location services, the app can determine when a commuter is at their rail station and distribute to the commuter a gift card code or ride voucher in the amount of their TNC subsidy level. Study administrators can then verify the use of the TNC mode by requesting participating commuters to submit screenshots of their TNC app and determine the role that TNC subsidies play in inducing mode shift for real commuters. Other options for a pilot study would be to partner with nonprofit transportation equity organizations to distribute TNC ride vouchers to community members who take rail for their commute or partner with major area employers to distribute TNC subsidies as a commute benefit or reimbursement.

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Appendix

A.1 Constant Parameters

Table A1. Constant Parameters for Four Bay Area Communities

Constant Parameters	*Symbol [Units]*	*Bay Area Communities*			
		San Francisco (Glen Park)	**Oakland (Lake Merritt)**	**Richmond**	**Orinda**
Walking Factor[1]	f_w [-]	1.09 [a]	1.03 [b]	1.18 [c]	1.61 [d]
Commuter Home Density[2]	δ [person/km^2]	2337 [e, f]	177 [g, f]	75 [h, f]	31 [i, f]
Distance from Rail Station to CBD[3]	L [km]	7.9	12.5	26.2	24.5
Speed of Car on Surface Street	$v_{c,st}$ [km/hr]	28.5 [j]	31 [k]	24 [l]	40 [m]
Cost of Gas and Maintenance for Car	c_g[$/km]	0.364 [n]	0.364 [n]	0.364 [n]	0.364 [n]
Cost to Park at Rail Station	$c_{p,r}$ [$/day]	6.00 [o, 4]	3.55 [p]	3.00 [q]	3.00 [r]
Cost to Park at CBD[5]	$c_{p,CBD}$ [$/day]	20 [s]	20 [s]	20 [s]	20 [s]
Walking Speed	v_w [km/hr]	4.4 [t]	4.4 [t]	4.4 [t]	4.4 [t]
Rail Speed	v_r [km/hr]	56 [u]	56 [u]	56 [u]	56 [u]
Rail Fare[6]	c_r [$/trip]	2.15 [v]	3.85 [v]	5.20 [v]	5.05 [v]
Rail Headway	h_r [hr/train]	0.06 [w, 7]	0.14 [w, 8]	0.13 [w, 9]	0.25 [w]
Bus Speed	v_b [km/hr]	15.7 [x]	20.3 [y]	20.3 [y]	38.6 [z, 10]
Bus Fare[6]	c_b [$/trip]	2.50 [aa]	2.25 [ab]	2.25 [ab]	1.00 [ac]
Bus Headway	h_b [hr/bus]	0.20 [ad, 11]	0.08 [ae]	0.50 [af]	0.50 [ac]
Bus Route Spacing[12]	S [km]	0.4 [ag]	0.25 [ae, ah]	1.3 [h, af]	5.7 [i]
Bus Stop Spacing[13]	s [km]	0.33 [ai]	0.25 [aj]	0.32 [aj]	0.61 [ak, al]
Radius of Community[14]	R [km]	1.25	1.75	1.37	3.06
Toll to Enter CBD	c_{toll} [$/CBD entrance]	0	7 [am]	7 [am]	7 [am]

Notes:

1. Ratio of WalkScore at rail station to WalkScore of 100
2. Commuter Home Density is equal to the community's population density multiplied by the proportion of commute flows traveling from the home county/city to the workplace county/city
3. All estimated distances from rail station to CBD using Google Maps distance measuring tool (https://maps.google.com/)
4. Parking costs $3.75 for 5 hours, so it is assumed $6.00 for 8 hours
5. Assume a monthly parking rate is used
6. Assume adult single-direction ticket
7. Average taken between 3 and 4 minute headways, weighted by likelihood of arriving during each (i.e., (3/7)*3 + (4/7)*4)
8. Average taken between 6 minute and 9 minute headways, weighted by likelihood of arriving during each (i.e., (6/15)*6 + (9/15)*9)
9. Average taken between 5 minute and 9 minute headways, weighted by likelihood of arriving during each (i.e., (5/14)*5 + (9/14)*9)
10. Distance traveled on route divided by scheduled times between points on route
11. Average between morning and evening frequency
12. Estimated average bus route spacing by taking square root of the community area and dividing by the number of bus routes that serve it
13. Average between minimum and maximum spacing for local bus service
14. Distance between adjacent stations on either side of a community using Google Maps distance measuring tool (https://maps.google.com/) divided by four

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All webpages accessed in March 2023.

A.2 Parameter Distributions

Table A2. Parameters Based on Distributions for Four Bay Area Communities

Parameter Distributions	*Symbol [Units]*	*Bay Area Communities*			
		San Francisco (Glen Park)	**Oakland (Lake Merritt)**	**Richmond**	**Orinda**
Value of Time[1]	ν [$/hr]	Reference a	Reference b	Reference c	Reference d
Desired Workplace Arrival Time[2]	α[hr]	Reference e	Reference f	Reference g	Reference h
Vehicle Ownership	ζ [-]	0.7[i]	0.83[i]	0.97[j]	0.97[k]

Notes:

1. Value of time calculated as annual income divided by 2000 (assuming 50 work weeks per year, 40 work hours per work week).
2. Used commute arrival time distribution between 6am and 9am. County commute data used when city data was unavailable.

Reference:

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c. https://data.census.gov/table?q=richmond+city+california+income&tid=ACSST1Y2021.S1901

d. https://data.census.gov/table?q=orinda+city+california+income&tid=ACSST5Y2021.S1901

e. https://data.census.gov/table?q=san+francisco+city+california+commute&tid=ACSST1Y2021.S0801

f. https://data.census.gov/table?q=oakland+city+california+commute&tid=ACSST1Y2021.S0801

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All webpages accessed in March 2023.

A.3 Derived Parameters

Table A3. Derived Parameters (Time-Varying Highway Speed) for Four Bay Area Communities

Derived Parameters	*Symbol [Units]*	*Bay Area Communities*			
		San Francisco (Glen Park)	**Oakland (Lake Merritt)**	**Richmond**	**Orinda**
Speed of Car on Highway	$v_{c,hwy}$ [km/hr]	• I-280N MP52.79 to MP54.11 • US-101N MP430.53 to MP432.54 • I-80E MP3.91 to 5.62	• I-880N MP41.65 to MP44.53 • I-80W MP1.5 to MP7.76	• I-80W MP1.5 to MP16.06	• CA-24W MP0.23 to MP6.47 • I-580W MP61.5 to MP62.83 • I-80W MP1.5 to MP8.07

Notes:

Caltrans Performance Measurement System (PeMS) used to estimate time-varying highway speed. Input milepost (MP) values for each highway segment, and used flow and density time-series data from March 2023 to estimate speed for morning and afternoon weekday commute hours.

Reference:

https://pems.dot.ca.gov/

All webpages accessed in March 2023.