Evaluating the Efficiency and Health Impacts of Next-Generation Transit System Design with Integration of Shared Mobility Services

Center for Transportation, Environment, and Community Health
Final Report

by

Yueyue Fan, Yunteng Zhang, Ran Sun

January 31, 2019

DISCLAIMER

TECHNICAL REPORT STANDARD TITLE PAGE

1. Report No.	2.Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Evaluating the Efficiency and Health Impacts of Next-Generation Transit System Design with Integration of Shared Mobility Services		5. Report Date November 28, 2018
		6. Performing Organization Code
7. Author(s) Yueyue Fan, Yunteng Zhang, Ran Sun		8. Performing Organization Report No.
9. Performing Organization Name and Address Department of Civil and Environmental Engineering University of California, Davis, California 95616		10. Work Unit No.
		11. Contract or Grant No. 69A3551747119
12. Sponsoring Agency Name and Address U.S. Department of Transportation 1200 New Jersey Avenue, SE Washington, DC 20590		13. Type of Report and Period Covered Final Report 9/1/2017 – 9/30/2018
		14. Sponsoring Agency Code US-DOT
15. Supplementary Notes		

16. Abstract

In the new mobility-as-service context, we envision that traditional system design principles of transit services shall be revisited to improve the overall system effectiveness. In this report, we will develop methods to quantify the effectiveness of a transit system, where private mobility services coexist, by measuring costs, social equity, environmental benefits etc. gained from active lifestyle. A real-world case study has been implemented to learn design and policy insights. While conducting this research, we also realized that the transit demand of a study area is often not available due to missing data. Since this is an important input for any network-based transit system design model, we also developed a method to infer missing transit demand via combing statistics and network modeling techniques.

17. Key Words	18. Distribution Statement
transit system, shared mobility, demand estimation	Public Access *[and if applicable, additional outputs (e.g. publications, IP, etc.)]*

19. Security Classif (of this report)	20. Security Classif. (of this page)	21. No of Pages	22. Price
Unclassified	Unclassified		

Form DOT F 1700.7 (8-69)

1. Introduction

Most transit systems in the United States face challenges of low ridership and high operating cost, even though ideally, by moving more people using fewer vehicles, public transit is supposed to play a much more critical role in achieving sustainability of a transportation system. Looking at the current transit agency practice and literature related to transit system design, typical evaluation criteria for transit planning and operations are the coverage of service area, user cost,operating cost and service quality, among others. (Sinha, 2003; Fan & Machemehl, 2006; Zhao & Zeng, 2007).

A typical issue causing low transit ridership is the “first mile, last mile” problem as it is not financially possible to build stops at every origin (Giannopoulos, 1989; TCRP., 1996). Many transit agencies have attempted to resolve those problems with special shuttles. However, shuttle services face even worse problems in terms of cost and ridership, leading to low and sporadic adoption of paratransit modes (Golden, Chia, Ellis and Thatcher, 2014; Enoch and Potter, 2016). At the same time, the development of mobile intelligent devices, like smart phones, has made low-cost ride sharing easily accessible in most urban areas. While transit agencies trying to improve the level of service, competition from ride-sharing companies is also driving a national transit ridership decline (Tyree, 2017).

The negative image associated with transit, such as empty buses, unreliable and infrequent service, heavy government subsidies, has been unfortunately a reality for many years. There are cultural, psychological, and land-used related factors causing low demand for transit, which would take much longer time to change, and are beyond the expertise of the PI and the scope of the proposed research. On the other hand, we envision that, with its advantage of scale, public transit ought to play a backbone role in the new environment of mobility as a service. The key ingredient that is urging and driving this transformation, is technology, which is changing the way people move around and interact with cities by giving people the ability to request, track and pay trips with mobile devices. From a system design viewpoint, can we do better to integrate public and private mobility services and to improve the overall system efficiency?

As a part of effort towards answering this big question, in this one-year project, we focus on reevaluating and redefining the role of public transit system and its design principle in the new context of technology and shared mobility. Specifically, we have evaluated the feasibility of an integrative system where public and private mobility service coexist to relax the conventional service coverage requirement of a transit system, so that the public transit resources can be reallocated more efficiently. Feasibility is measured by cost (including user cost and agency cost), social equity (impact on different user groups), and environmental benefit (measured by energy and emission savings per person-mile-traveled). We use transit system of Santa Clara County as a real-world case to study the feasibility. In addition, as we start to look more in depth into building a system model for simulating users’ choices in the multi-modal network where private and public mobility service providers coexist, we realized that a critical input was missing, which is the actual transit demand. In the second half of our project duration, we began developing a transit demand estimation model, which is also included in this report.

2. Financial Feasibility Analysis

The ridership data of Santa Clara Valley Transit Agency (VTA) showed that some rarely used bus stops and routes were kept in the system mainly to fulfill the service area coverage requirement. Relaxing such constraint has long been considered socially unacceptable because there are individuals and communities largely relying on transit. In this section, we mainly consider whether it is financially viable to replace some ineffective transit routes by private mobility services. The analysis of financial feasibility is done based on statistical analysis of operating data including ridership and fiscal data.

Most of the results reported in this study were obtained based on statistical analysis of the following data:

Table 1. Datasets and Sources

Dataset	**Source**
Adopted Budget Fiscal Year 2016-2017	Provided by Santa Clara VTA
Ridership Data	Santa Clara VTA website
Transit Routes Map	Santa Clara VTA website

2.1. Assumptions

Our investigation of the feasibility of an integrative system combining shared mobility services and public transit were based on the following assumptions:

Static and known transit demand

In this study, we use existing transit demand as a fixed known input parameter to the feasibility analysis. Ideally, we understand that introduction of ride sourcing services to the system may change travelers' travel behavior in terms of trip rates, mode choice, and route choice, thus changing the actual travel demand. For example, for each trip combining public transit and shared mobility, part of the trip happens in private cars, the comfort will be increased. At the same time, ride-sharing apps on mobile devices can guarantee easy access to shared mobility services so that people can replace the original low frequency transit with shared mobility, leading to reduced waiting time, improved flexibility, accessibility and reliability. If the extra cost of using ridesourcing services is covered by some subsidy mechanism, we can expect an increase in transit demand. However, given the limited time and resources provided by this seed grant, it is unrealistic to build a full-scale endogenous behavior model in the feasibility study. Therefore, we use existing transit demand to quantify the system users, and then carry a sensitivity study to test how deviation from this assumption may affect the conclusions.

Developing a business model that accommodates strong public-private partnership is possible

Another assumption is that it is possible to develop a financial mechanism to redistribute revenues among shared mobility and public transit. We assume public transit operators can develop and use such mechanism to compensate target passenger population so as to minimize the inconvenience caused to them by removing a transit route. Although this paper does not delve into the mechanism design in depth, considering the capability of mobile devices nowadays, we are optimistic that this assumption is implementable. On the other hand, already existing practice in Seattle demonstrates the possibility of combining UBER and transit system (Clugston, 2017).

Easy accessibility to shared mobility service

This paper assumes that after a transit route is removed, the transit system can maintain its level of service by compensating passengers for the usage of shared mobility services in the originally covered area. However, many of the selected candidate routes for removal, where there is less demand for public transportation, are actually located in remote area. And there may not be enough supply capacity of shared mobility in those areas. Therefore, after removing those transit routes, passengers may not be able to easily access shared mobility, so that the level of service may be reduced. Shared mobility companies such as UBER will need to further research to explore if increasing the availability of shared mobility in these areas by giving drivers bonus is financially sustainable, which is beyond the scope of this study.

Origin and destination are transit stops

Due to the lack of actual origin and destination (OD) information, we assume that each trip begins or ends at the first and last transit stops where passengers board or get off.

2.2. Financial Feasibility Analysis Procedure

The step-by-step procedure for evaluating the financial feasibility of integrated, multimodal public transportation system and private shared mobility is provided in Table 2:

Table 2. Feasibility Analysis Procedure

Steps	**Details**
Statistical Analysis of Raw Ridership Data	Calculate the total, average, variance of on and off ridership at each stop Obtain rider volume of each transit routes
Filtering transit routes	Criteria includes: Low average ridership Large cost per rider Available nearby alternative transit routes
Manually observe and select candidate routes	For example, if most of riders get on board in the first or last few stops of a transit route, the demand is more concentrated at both ends. This kind of transit route can be more easily replaced by transporting passengers using shared mobility to nearby alternative transit routes.
Calculate the operating cost saved by removing the entire or a part of the transit route.	Calculated based on fiscal data from Santa Clara VTA
Calculate the amount of riders that need to be subsidized for shared mobility cost to maintain the level of service of transit system for this group of passengers. Calculate the maximum amount of compensation can be provided to each rider for each trip.	

A threshold for low average ridership is set to be 16.95 passengers per vehicle trip. This value is calculated based on the average bus fuel economy, 2.33 MPG, the average private car fuel economy, 25 MPG and the average ridership per private car trip, 1.58 passengers per vehicle trip (Lowe, Aytekin and Gereffi, 2009; Foxall, 2016). As we seek to improve the environmental sustainability, we do not want to simply gain financial efficiency at a cost of more environmental damage. In order to lower GHG and other related emissions, we seek to achieve a high overall fuel economy per passenger, that is, 25 MPH × 1.58 / 2.33 MPG = 16.95 passengers per vehicle trip.

The threshold for large cost per rider is set to be $7.39 per trip. In this research, we consider possible removal of a transit route with low ridership, whose demand is then covered by combining private mobility services and nearby transit routes in good ridership condition.

The last criteria, available nearby transit alternatives, is easy to understand. We account for all available transit services within a proximity of 3 miles of the origin or destination a travel demand, and consider using a shared mobility service to connect the missing dots. This 3-mile shared mobility service translates to an additional cost of $7.39.

2.3. Results

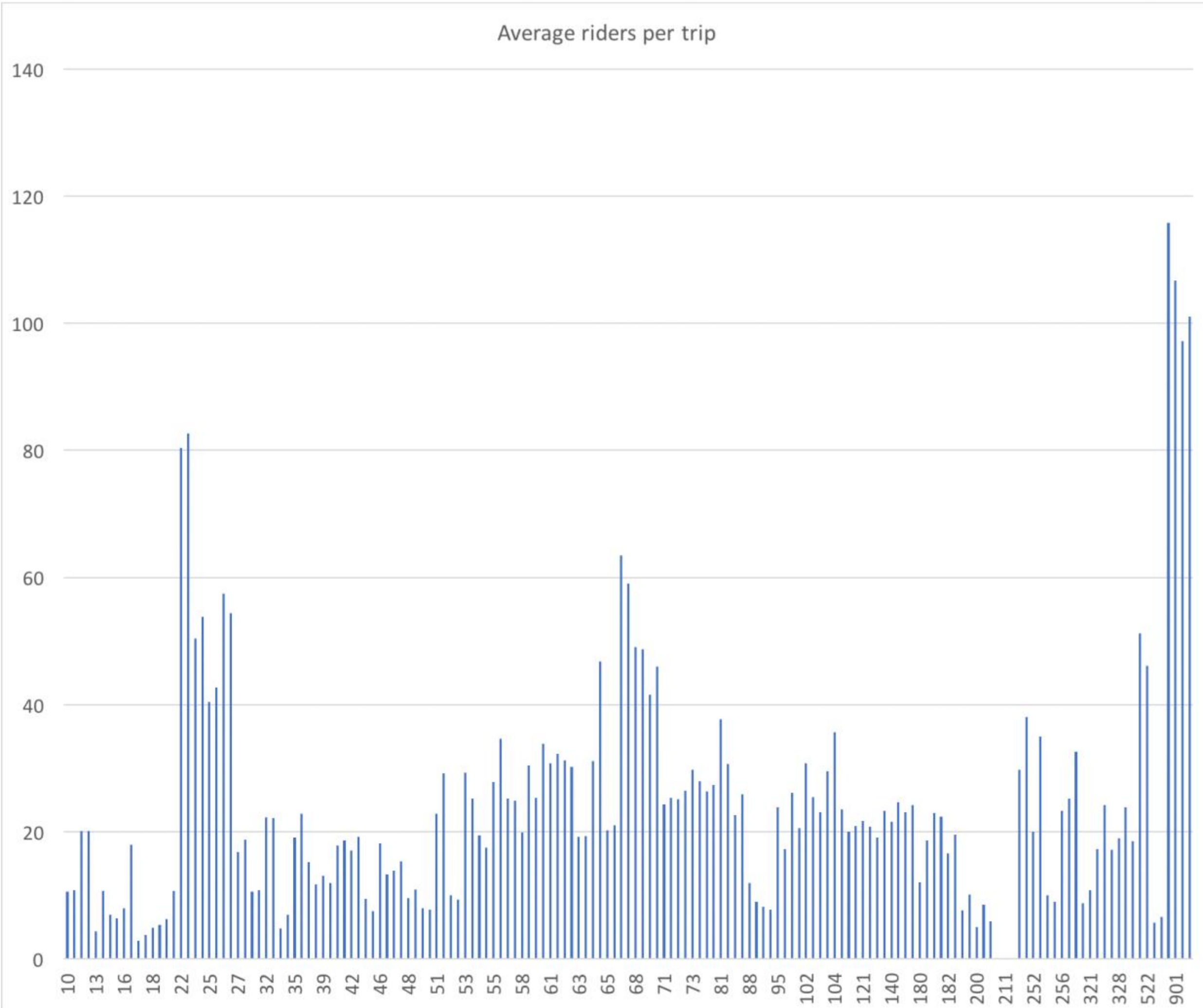
The overall ridership performance of all VTA routes in Santa Clara County is summarized in Table 3.

Table 3. Overall ridership performance of VTA operated transit routes

Item	**Results**
Maximum ridership per vehicle trip	115.79 (carried by line 901)
Average ridership per vehicle trip	24.32 (with standard deviation of 19.34)
Range	0 – 115.79

Below is a figure showing the average ridership of all transit routes in Santa Clara County:

Figure 1. Average Ridership of Transit Routes



As can be seen from Figure 1, the average ridership of each transit route varies significantly. From manual observation on locations of each route and description of routes by Santa Clara VTA, the authors found out most of low ridership routes are operated to satisfy demand of lower density areas.

With the analysis procedure described in Section 2.2, we identified a set of transit routes that are low in ridership and have high average cost per rider (there are about two dozen, only 7 of them are listed here for demonstration purpose):

Table 4. A list of identified transit routes for potential removal

Transit Route	**Average Ridership (passengers per vehicle trip)**	**Gross Cost per Rider (dollar)**	**Gross Cost Saved (per year, dollar)**	**Route Type**	**Nearby Alternative Transit Route**
46	13.61	8.00	229438	Local	66, 70, 71, 180
52	9.34	9.18	346173	Local	40
900	6.15	12.63	1282159	Light Rail	Not needed
321	9.76	12.63	21088	Limited	60, 104, 902
185	8.92	63.57	56082	Express	32, 68, 104, 522, 902
17	3.33	22.78	155010	Community	14, 68
200	4.97	26.96	28207	Other	104, 902

Figure 2 shows the average cost per rider of those poorly performing routes.

Figure 2. Average Gross Cost per Rider

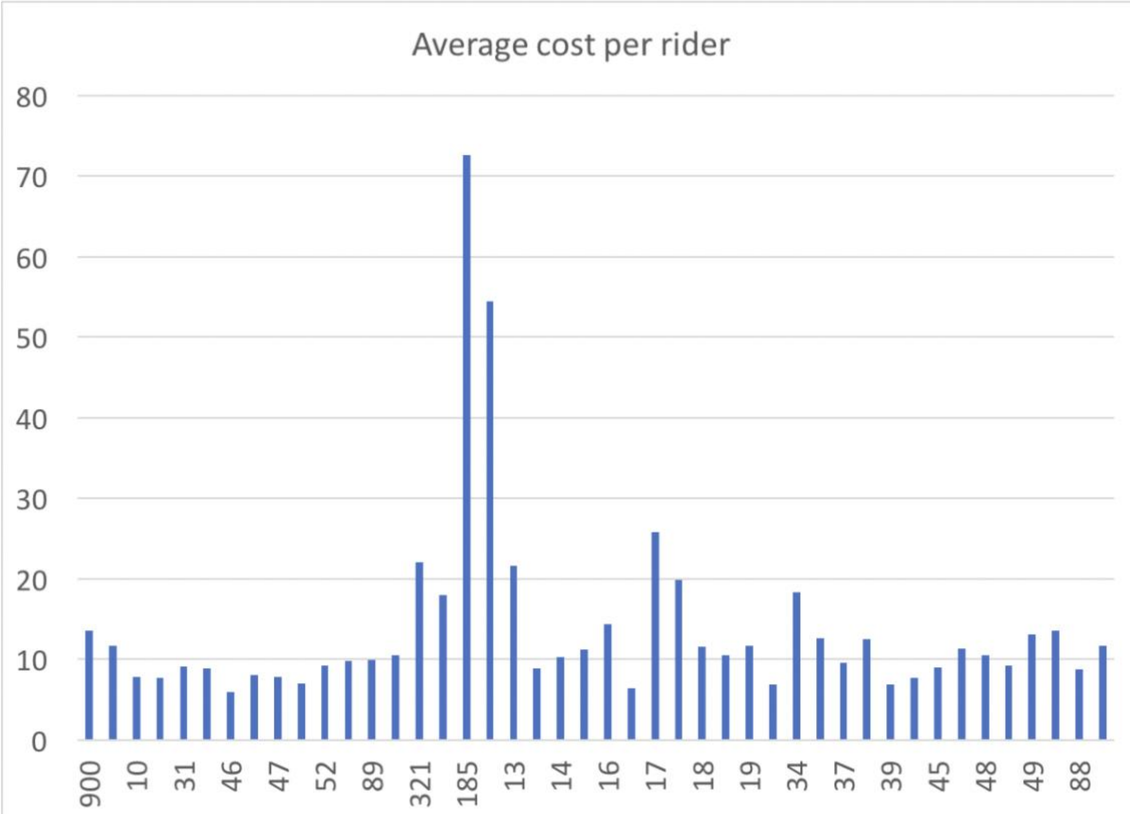


Table 5 summarizes the ridership performance by route types.

Table 5. Ridership performance by route types

	All	Low ridership routes* (Number and %)	Large average cost routes** (Number and %)	Low ridership & large average cost routes* (Number and %)
All routes	72	27 (38%)	56 (78%)	25 (35%)
Core routes	18	0 (0%)	6 (33%)	0 (0%)
Local routes	17	8 (47%)	13 (76%)	6 (35%)
Community routes	16	13 (81%)	16 (100%)	13 (81%)
Express routes	13	3 (23%)	13 (100%)	3 (23%)
Light rails	3	1 (33%)	3 (100%)	1 (33%)
Limited routes	4	1 (25%)	1 (25%)	1 (25%)
Other	1	1 (100%)	1 (100%)	1 (100%)

*Low ridership indicates the average ridership is below 16.95 passengers/vehicle trip
**Large average cost indicates the average cost per passenger trip is over $7.39

We then explored the possibility of reallocating saved transit budget to subsidize target passenger population for shared mobility trip of up to 3 miles. As can be seen from Figure 2, the average cost per rider of most of routes can actually accommodate shared mobility trips of up to 5 miles. And if we look at the budget of operating all the routes shown above as an entity, averagely we will have higher capacity of subsidy. Therefore, there is a great financial potential to support building up the integrated multimodal system as we envision.

Figure 3 is a map showing the transit routes mentioned above with different colors indicating the maximum amount of subsidy for every rider who has been using the transit routes.

Figure 4 shows what other alternative routes can be accessed within 3 miles of stops of lower ridership routes. As can be seen from the map, within 3 miles, there are many routes available as alternative options.

Figure 3. Routes with low ridership and high rider cost

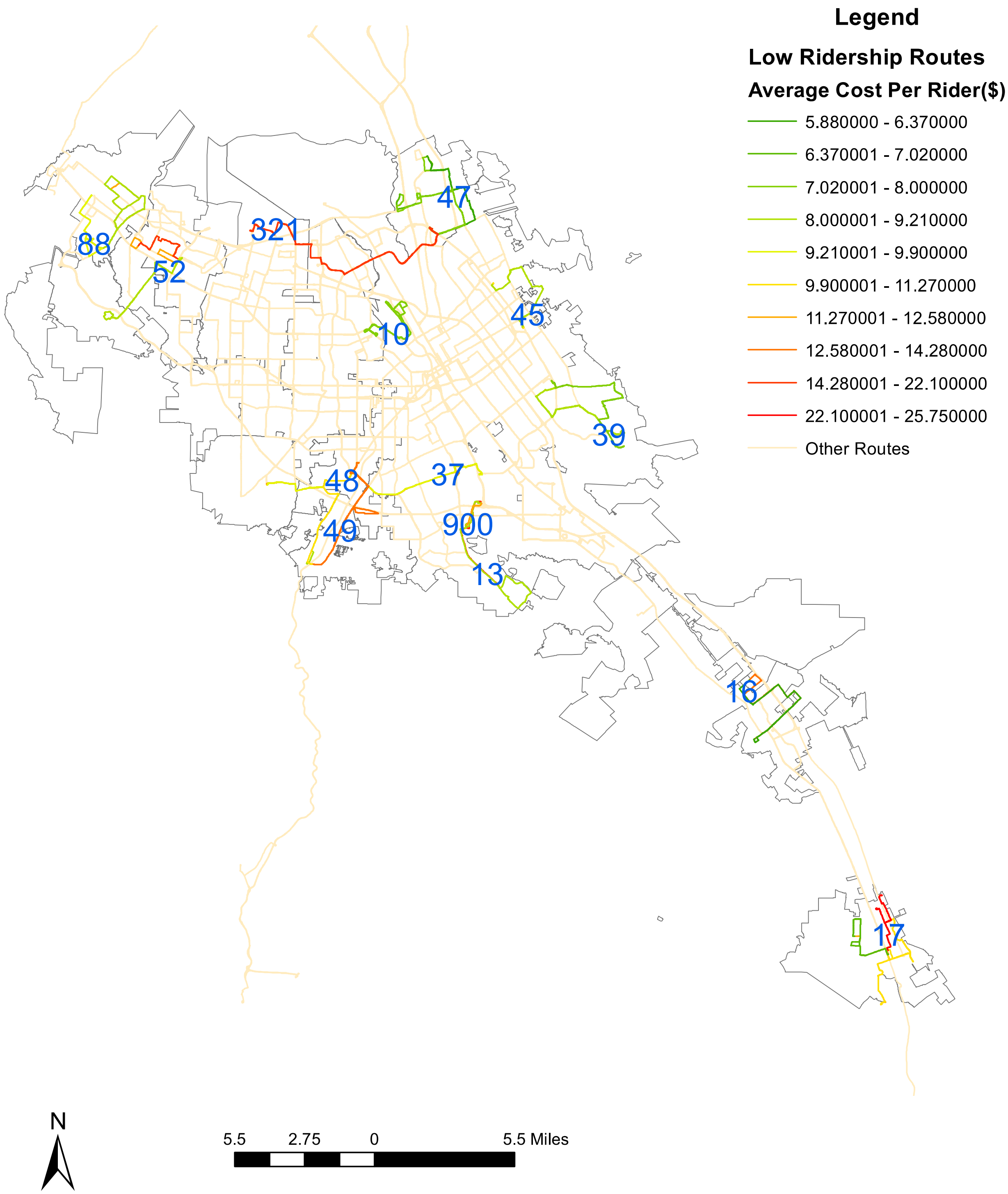
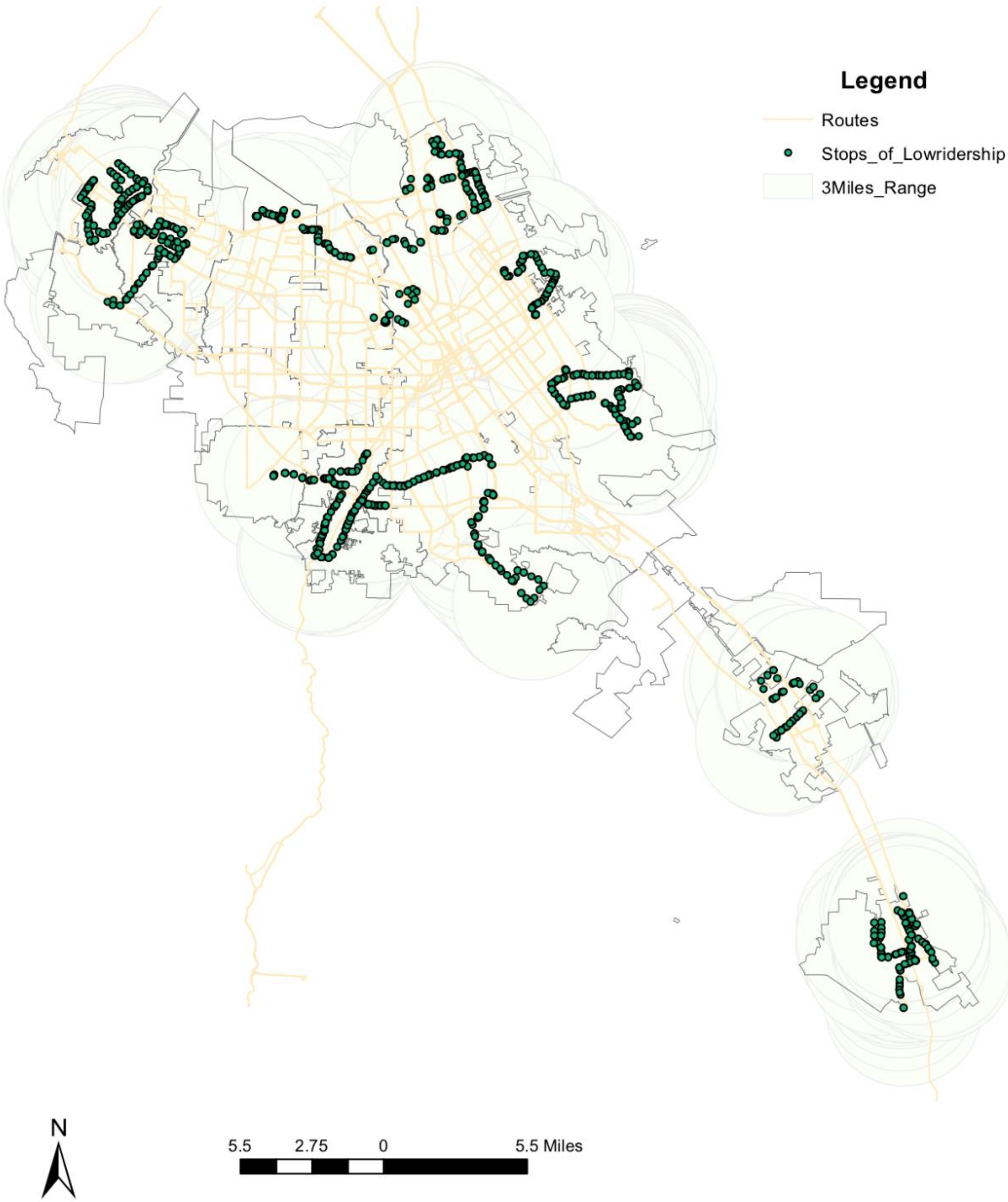


Figure 4. Alternative Routes within 3 miles



2.4. Detailed Analysis of Certain Typical Bus Routes

The following transit lines are chosen for a further detailed analysis as an illustration of the financial feasibility.

Route 46 (Local route)

Santa Clara VTA operates numerous bus lines that operate on most major thoroughfares throughout Santa Clara County. Those lines are called Local routes.

As a local route, route 46 is operating at a relatively good condition, where the average ridership is not much below the low ridership threshold and the average rider cost is not much above the large cost threshold. However, most of coverage of Route 46 can be covered by Routes 66, 70, 71 and 180. In addition, as the entire length of Route 46 is about 6.5 miles, translating into a ridesourcing cost of about $9.8, based on the average cost per rider of $8 per rider trip, combining ridesourcing and Routes 66, 70, 71 and 180 can well satisfy the demand that current is using Route 46.

The majority of Local routes face a problem of high cost, but considering their ridership situation, most of them are actually operating well in terms of trade-off between environment sustainability and cost efficiency.

Route 321 (Limited route)

This type of route basically operates on weekdays only (except holidays), mostly during peak hours. These routes operate via expressways to provide semi-express service to industrial parks in Sunnyvale and Milpitas.

The intension of Limited routes is well justifiable, but the ridership and cost of Route 321 do not match its purpose. Route 321 is the only route among all Limited routes that suffers low ridership and large cost. Based on the nature of the route, and the fact that coverage of Route 60, 104 and 902 overlap most of its coverage, it is reasonable to replace Route 321 by the combination of ridesourcing services and other routes.

Route 900 (Light rail)

This type of routes are intercity routes operated in conjunction with other agencies.

Due to the short length of Route 900, which is about 1.2 miles, we cannot find other suitable alternative routes for it. Considering the average cost per rider is $12.63, it can be well replaced by subsidized ridesourcing option.

Route 900 is the only one among all Light rail routes that suffers lower ridership and cost efficiency. Though the other 2 Light rail routes may have cost efficiency issues, their riderships are high and this makes them suitable to continue serving the public.

Route 185 (Express route)

Express routes mostly operate during weekday peak hours only. These routes operate in two patterns: AM commute and PM commute. AM commute operates towards industrial parks, Downtown San Jose, or Fremont BART, while PM commute operates from industrial parks, Downtown San Jose, or Fremont BART.

Most Express routes are operating well in terms of ridership, though their cost efficiency can be further improved. Route 185 and other two Express routes are suffering low ridership and large cost. For each of the three problematic routes, there are a couple of other transit routes that can work as alternatives if connected with shared services. Due to their large average cost ($63.57 per rider for Route 185), it is reasonable to replace them with integrated services.

Route 17 (Community route)

Community routes are operated by VTA mainly to serve lower-density communities, in which regular transit services do not justify such operations, because of area geography or low ridership.

As a community route, Route 17 is relatively short. Considering the large average cost per rider, which is $22.78, and the short range of the route, it can be well replaced with subsidized private mobility services. On the other hand, services of Route 14 and 68 can actually satisfy most demand covered by Route 17. Note that most of community routes are the same as Route 17.

Route 200 (Light rail shuttles)

This type of shuttles mainly operates to and from light rail stations around San Jose. These services use shuttles instead of regular buses, thus the fuel economy is better, about 8 vehicle miles per gallon. With some calculation, we can figure out that in terms of environmental concerns, the average ridership of Route 200 makes to private cars. The average cost per rider trip is $26.96, which is much more expensive than most normal ridesourcing services, like UBER. Considering the service range of Route 200, which is about 9.8 miles in total, operating Route 200 is not financially efficient. It would be better off if we just replace the service with ridesourcing services as an UBER trip of 9.8 miles takes about $13.95.

Core routes

Core routes belong to Local route category, except that they cover key transfer points, including Downtown San Jose, several Caltrain stations between Palo Alto and Gilroy, and most light rail stations. Some of them also provide connecting services to other transit agencies, including AC Transit, Dumbarton Express, Monterey-Salinas Transit, and SamTrans.

The nature of Core routes makes them operate quite well in Santa Clara county. All of them have pretty healthy ridership and most of them are cost efficiency.

2.5. Relevance to Sustainable Transportation

Ideally, transit system can significantly reduce GHG emissions. If a bus is fully loaded, with fuel economy of 2.33 vehicle miles per gallon and 50 capacity, the equivalent fuel economy is about 117 passenger miles per gallon, which is much higher compared with the average fuel economy of private cars, 25 MPG, with only one passenger in vehicle (Lowe, Aytekin and Gereffi, 2009; Foxall, 2016). However, as shown in the results above, it is not the case in Santa Clara county because about 1/3 of transit vehicles are running with their average ridership smaller than 16.95. Mathematically, it translates to 39.49 passenger miles per gallon. On the other hand, averagely there are 1.58 passengers per private vehicle trip (Lowe, Aytekin and Gereffi, 2009), translating to 39.5 passenger miles per gallon, which is expected to be even higher with the development of shared mobility services. Therefore, in the case of Santa Clara county, even if it were not for the economics reason, it is theoretically more environmentally favorable to replace about 1/3 of their transit routes with private cars.

In an integrative system, we envision that transit routes with lower ridership are removed, partially or in its entirety, or having reduced frequency during off-peak hours. This could potentially improve the average passenger fuel economy for the entire transportation system. Therefore, an integrative transit system will be significantly beneficial in terms of environment sustainability.

2.6. Other Considerations

Legal Concerns

Ridesourcing companies, such as UBER, hire drivers without offering them formal employment. This kind of business model makes drivers independent contractors who can be provided incentives, but cannot be subject to employment conditions. This raises several difficulties for ridesourcing companies getting contract supported by federal funds to provide paratransit services (Murphy, 2016; Cunningham, 2016).

According to (Nelson\Nygaard Consulting Associates, et al, 2007), for any party contracted with public transit agencies to provide mobility services, drug and alcohol test is required. It is hard to fulfill drug and alcohol testing requirement because of the independent nature of drivers with the ridesourcing services.

Ridesharing companies do not have fleet-level accessibility accommodations. No matter transit vehicles or paratransit vehicles, they shall all be deemed to provide equivalent service if the service is made available to individuals with disabilities, including individuals who use wheelchairs (49 CFR 37.77). Examples of the accommodations are as shown in Figure 5. On the other hand, there are difficulties to educate and occupationally train drivers to help load/unload passengers with impaired mobility and secure their wheelchairs properly (Murphy, 2016).

Figure 5. General ADA Accommodations Provided by Public Transit Vehicles

All the legal issues aforementioned are under litigation in several jurisdictions in the U.S. As the social and environmental benefits are remarkable, and the tremendous profits are attractive to ridesourcing companies, the ridesourcing companies, the government (including the court and public transit entities) and the general public are more likely to make an effort to reach an agreement eventually. As technologies advance at their own pace, we envision that the transportation world is going to go through a major technology transformation. Any party who is not making a deliverable effort to keep up with the change is likely to fall behind or out of the game eventually. Since there are mutual benefits gained by all parties, we are optimistic that a better integrated system will form given better coordination and fair revenue sharing mechanisms among those parties.

Political Concerns

As mentioned in Section 3.2, in this study, the authors assumed an overall good availability of ridesourcing services. However, this is certainly not the case in reality. Due to the nature of ridesourcing drivers that they are not subject to employment, they provide services based on their own interest of incentives instead of duty requirement. If the incentives provided by ridesourcing companies are not attractive enough, low density communities may be lack of sufficient ridesourcing supply capacity to meet the level of service desired. Some existing practices in major cities in the U.S. show promises to overcome this issue (Salzberg, 2017). By providing riders incentives to use ridesourcing services as connection between their origin/destination to transit stations, ridesourcing companies can increase rider demand in low density areas so that drivers have more incentives to serve those areas. Cooperation between transit agencies and ridesourcing companies, such as current pilot practice in Seattle (Clugston, 2017), demonstrates a way that mobility agencies can maintain or improve level service in an integrated system.

All in all, even though the level of service requirement may be challenging, great potential can still be seen in existing practices attempting to integrate public transit and private mobility services.

Equity Concerns

According to (Neff and Pham, 2007), lower income riders are more likely to use transit mode. Due to the features of lower income groups and certain other demographic groups, such as elderly aged group, the level of service different demographic groups will receive after transition to an integrated public transportation system varies significantly. This may cause Equity concerns. One of the equity concerns is raised from accessibility of communication technology. The development of mobile devices has proved to significantly improve rider experience among all kinds of modes and trip purposes, and at the same time have significantly increased the use of transit modes (Ferris, Watkinsand Borning, 2011; Windmiller, Hennessy and Watkins, 2014; Gooze, Watkins and Borning, 2013). Meanwhile, the development of technology has also brought opportunities for building an integrated multimodal public transportation system. However, to build such a system, from a system design viewpoint, in order to meet equity requirements, designers must consider the methods that various groups of residents access information about public transit and other mobility options. According to (Windmiller, Hennessy and Watkins, 2014), certain demographic groups tend to not own smartphones and therefore they are not able to access transit information via mobile devices, especially elderly and low-income people. At the same time, the situation has been improving - more and more people begin to use smartphones and other alternatives have been developing for better accessibility. In the context of building the integrated system, built based on the groundwork of a strong public-private partnership, it is reasonable to expect that transit agencies and ridesourcing agencies can accommodate certain demographic groups by developing a requesting, tracking and dispatching system, and/or conducting outreach activities to educate residents about alternative solutions.

3. Estimation of Transit Demand

Transit systems in the U.S. are suffering from declining ridership. A large portion of regular bus systems are not equipped with electronic payment cards; hence it is difficult to trace passengers travel pattern. However, automatic passenger counting (APC) system is utilized by most transit agencies in California, where numbers of boarding and alighting at transit stops can be recorded. Transit travel demand estimation is a crucial part to understand the behavior of transit users and serve as a critical input to any model aiming to improve the overall transit system efficiency. Typically, OD demand estimation can be viewed as an ill-posed inverse problem of a traffic network assignment problem because the number of OD pairs is generally much larger than that of links where traffic counts can be collected. in this study, we developed a stochastic transit demand estimation framework. Structural information of multi-day observations as well as network topology are preserved through the process. This framework inherently incorporates demand parameter estimation and trip table reconstruction processes, where various transit travel behavior and estimation principles can be applied. Accordingly, equilibrium transit assignment and generalized least squares method are implemented under the proposed hierarchical estimation framework. At last, numerical examples are illustrated based on an example transit network.

3.1. A Transit Network

A transit network can be described as a directed graph *G(N, L)*. *N* is the node set, i.e. transit stops, where passengers can board and alight; and *L* is the link set, representing transit segments.

Chriqui and Robillard (1975) assumed that transit users traveling from one stop n_i to another stop n_j, will only consider a subset of common lines A_{ij} to minimize expected travel time. And this traveler will board the first arriving transit vehicle in common lines set A_a for a specific modified link a. Assume a transit line with frequency f_l and in-vehicle travel time t_l, waiting time is assumed to be an independent random variable with mean value of $1/f_l$. Accordingly, the common line set A_a can be determined based on the solution from

$$\begin{aligned} &\underset{I_l}{\operatorname{argmin}} \frac{1+\sum_{l=1}^{s} t_l f_l I_l}{\sum_{l=1}^{s} t_l I_l} \\ &\text{s.t.} \qquad I_l \in \{0,1\}, \forall\, l \in A_a \end{aligned} \tag{1}$$

where s is the number of parallel transit lines connecting two consecutive nodes. And a transit line l can be included into the common line set if $I_l = 1$, and will not be considered as a travelling link choice by transit users.

Based on common line set, the transit network can be constructed using route section representation *G(N, A)*, more details can be found in De Cae and Fernández (1993). Link $a \in A$ is the route section connecting two connecting nodes $(i, j), i, j \in N$ and $i \neq j$. A route section is a link from the common line set A_a containing one or several transit lines between two consecutive transfer stops. Path r is the combination of non-cyclic links from origin node and destination node. $w \in \boldsymbol{W}$ is OD pair. R_w is the set of paths connecting OD pair w. Link flow v_a is the flow through link $a \in A$, path flow h_r is the flow through path $r \in R$. x_w is OD demand or OD flow of OD pair w. k is one observation time period in a total time K.

From the network topology standpoint, the relation between OD flow x and path flow h can be expressed in a matrix form,

$$\boldsymbol{x}^k = \boldsymbol{\Gamma}^k \boldsymbol{h}^k, k = 1, 2, \dots, K \tag{2}$$

Where OD flow is $\boldsymbol{x} = [x_w] \in \mathbb{R}^n$, $\boldsymbol{h} \in \mathbb{R}^R$ is path flow vector. Besides, link flow $\boldsymbol{v}$ and path flow $\boldsymbol{h}$ have relation

$$\boldsymbol{v}^k = \boldsymbol{\Delta}^k \boldsymbol{h}^k, k = 1,2, \dots, K \tag{3}$$

Where link flow vector is $\boldsymbol{v} = [v_a], \forall a \in A$ and $\boldsymbol{v} \in \mathbb{R}^L$. Γ is OD-path incidence matrix, component $\gamma_{wr} = 1$ if route r connecting OD pair w. Clearly, Γ is of full row rank, since each path must belong to one and only one OD. Δ is link-path incidence matrix, similarly component $\delta_{ar} = 1$ if link a is on path r. Obviously, path flow $\boldsymbol{h}$ is the crucial bridge between link flow and OD flow.

APC records the number of passengers boarding i_n and alighting o_n at stop n. In an APC-enabled transit network environment, link flow count for all of the links $a \in A$ can be obtained by enumerating ridership along transit lines. For a specific transit route, one can accumulate the number of boardings and then subtract the number of alightings at stops along the transit route starting from the first node, usually terminal bus station, to the interested node in the route. Therefore, we can have the link flow of $a \in A$ as

$$V_a^k = \sum_{f \in F} \sum_{n=1}^{n*} (i_n^{kf} - o_n^{kf}) \tag{4}$$

Where i_n is the number of boardings at stop n, and o_n the number of alightings at stop n. $n*$ is the tail node of interested link a, f is a specific transit run in observation day k with total daily runs F.

3.2. Transit Network Operation

Traffic assignment considers travelers' route choice behavior in a transportation network based on generalized cost or utility, usually including travel time, waiting time, discomfort, fare, convenience and other factors. All of the transit users are considered to be identical in this study, therefore, they share similar disutility structure.

In a single-mode transit network, path flow assignment mapping can be expressed as,

$$\boldsymbol{h}^k = G^l(\boldsymbol{x}^k), k = 1,2, \dots, K \tag{5}$$

Both stochastic user equilibrium (SUE) and multinomial logit model (MNL) fall into path-based traffic assignment paradigm, since the routing behavior is based on travelers' relative disutility. Furthermore, by incorporating link-path relationship, path flow assignment can be transformed into link flow assignment mapping,

$$\boldsymbol{v}^k = G^l(\boldsymbol{x}^k), k = 1,2,\dots,K \tag{6}$$

In a congested transit network, passenger overload delay should be endogenously determined in the equilibrium state. Link cost can be decomposed into,

$$c_a = t_a + u_a \tag{7}$$

Where t_a is in-vehicle travel and u_a is waiting time on link a.

Logit-based Stochastic user equilibrium (SUE) with capacity constraints can be formed as (Lam et al., 1999),

$$\begin{aligned} \min \quad & \beta \sum_{a \in A} (c_a) v_a + \sum_{w \in W} \sum_{r \in R_w} h_r (\ln h_r - 1) \\ \text{s.t.} \quad & \boldsymbol{x} = \boldsymbol{\Gamma h} \\ & \mathbf{v} = \Delta \boldsymbol{h} \\ & \boldsymbol{v} \leq Ka \\ & \boldsymbol{h} \geq \mathbf{0} \end{aligned} \tag{8}$$

Where Ka is the capacity vector, of the same dimension of number of links L, β is calibration parameter.

3.3. Transit Demand Estimation

The resulting link proportional assignment matrix G_p^k from SUE is introduced into demand estimation framework as exogenous parameter. We use generalized least square (GLS) estimator to estimate the transit OD demand. The interested question is to estimate the mean $E[\boldsymbol{x}|\theta]$ and reconstruct $\boldsymbol{x}^k$. GLS is used widely for mean estimation where $\theta = E[\boldsymbol{x}]$. Let $\xi^k = \theta - \boldsymbol{x}^k$ denote the deviation of link count on day k. $\boldsymbol{z}^k = \boldsymbol{v}^k + \boldsymbol{\epsilon}^k$ is observed link count with noise ϵ.

The proposed stochastic demand estimation program is

$$\begin{aligned} \underset{\theta, x^1, x^2 \dots x^k}{\text{argmin}} \quad & \lambda(\boldsymbol{X} - \theta)^\top (\boldsymbol{X} - \theta) + \mu(\boldsymbol{X} - \theta)^\top (\boldsymbol{X} - \theta) + \omega(\boldsymbol{Z} - \boldsymbol{V})^\top (\boldsymbol{Z} - \boldsymbol{V}) \\ \text{s.t.} \quad & \boldsymbol{G}_p \boldsymbol{X} = \boldsymbol{V} \end{aligned} \tag{9}$$

Where $\boldsymbol{X}, \boldsymbol{V}, \boldsymbol{Z}$ are vectors of OD demand, true link flow and observed link flow with k days' observation, respectively. And $\boldsymbol{G}_p$ is a design matrix for proportion assignment of total Kdays' observation, $\boldsymbol{G}_p = \begin{bmatrix} G_p^1 & & & \\ & G_p^2 & & \\ & & \cdots & \\ & & & G_p^k \end{bmatrix}$.

3.4. Numerical Experiments

Consider an example network show in Figure 6, consisting of 7 links and 4 nodes. It is served by 4 transit routes. Using route-section representation, this transit network can be transformed into a modified network with 6 route-section links, as shown in Figure 7.

Figure 6. A small example of a transit network

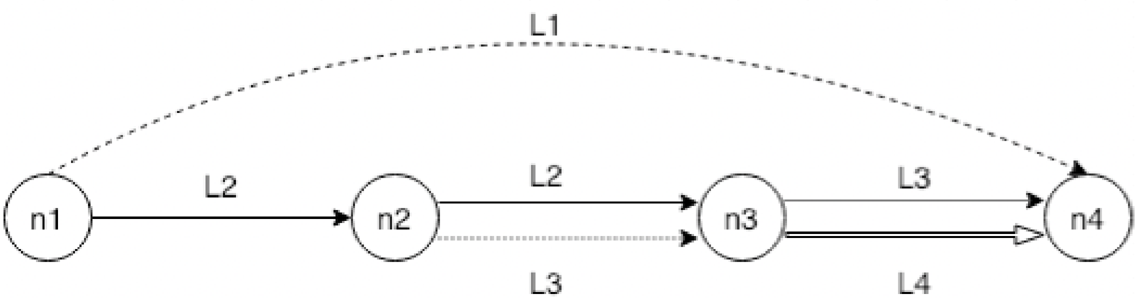
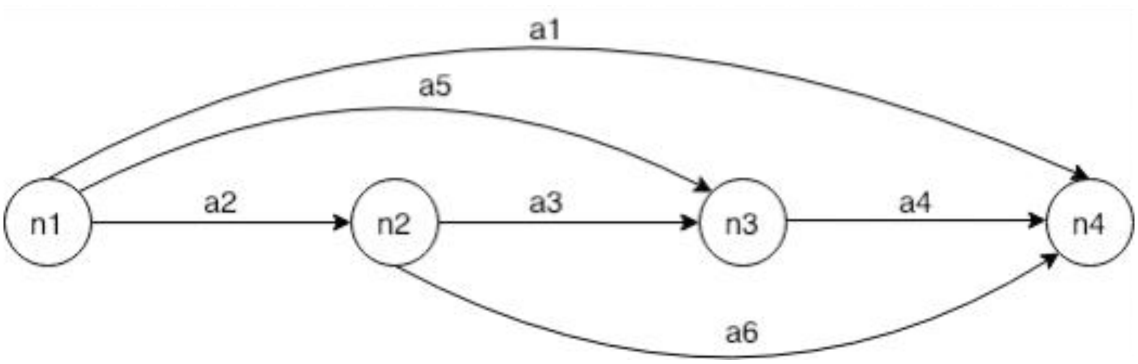


Figure 7. Modified route section representation network



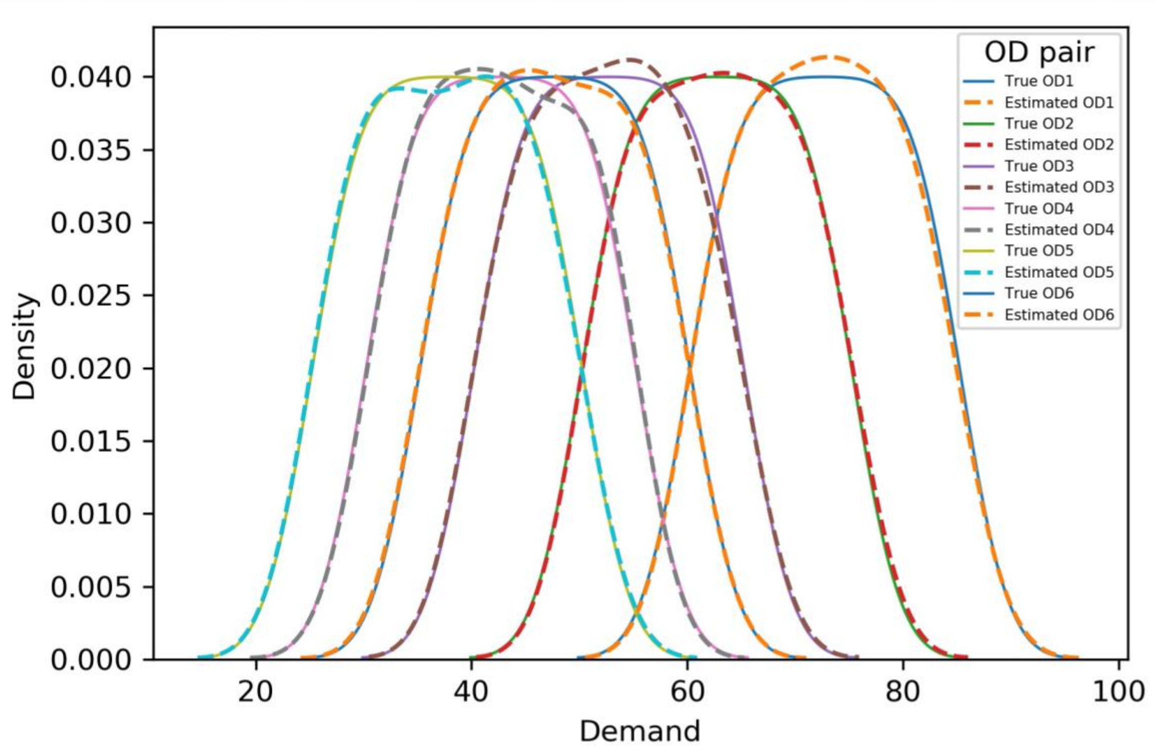
We are interested in a time horizon containing 250 observation time periods, usually morning peak hour. OD demand samples are generated using normal distribution for 250 observation time windows, and accordingly, observed link counts are obtained based on SUE transit assignment rule. Since transit timetable is usually stable in a reasonable time period, we assume the link attributes and cost parameters to be fixed in the analysis time horizon. The link data input of the transit network is given in Table 6.

Table 6. Travel cost input

	a_1	a_2	a_3	a_4	a_5	a_6
In-vehicle time (min)	30	24	10	12	10	20
Waiting time (min)	6	6	3	6	6	6
Link capacity (pass/hr)	100	100	150	250	100	50

In this example, 50 samples of true OD demand are normally generated. The comparison between the true and the estimated OD for different OD pairs is plotted in Figure 8. For this simple numerical case study, the proposed stochastic demand estimation method has resulted in good quality estimation results. For future study, more work is needed including testing a moderate to large scale transit network and incorporating variance estimator in the stochastic estimation program.

Figure 8. Comparison between true and estimated demand for different OD pairs



4. Conclusion, Discussion, and Future Research

Based on the discussion and analysis results gained from the Santa Clara case study, we can conclude that an integrated multimodal public transportation can be financially feasible, accompanied by significant sustainability benefits. We can expect improved level of service brought by improved rider experience, increased flexibility, availability and reliability. On the other hand, there are still obstacles raised from legal, political and equity concerns. Given in-depth review of most recent studies and existing successful practices in some cities, it is hopeful that these barriers may be overcome through a better coordination/cooperation among different entities in the system.

Due to the limited time and resources provided by this seed grant, there are several interesting remaining questions yet to be investigated in more depth. For example, in the case study, we have shown that if the transit agency could subsidize each rider trip for at most a 3-mile ridesourcing trip, the overall system can still gain a better economic efficiency. Along this direction, researchers may further explore how to optimally design a subsidy strategy that could improve the overall transit users' benefits or the overall system performance.

A more in-depth investigation on this question would require a model that could capture the interactions among multiple entities (transit agency, private mobility service providers, and transportation system users), which would impose high modeling and computing challenges. Also, as discussed above, the demand is expected to increase because of improved rider experience and level of service. Increased demand will require more subsidy, and whether it will still be financially feasible remains a question that is worth further research. Upon dynamic demand being well studied, researchers may consider further studies on operating strategies of transit agencies and shared mobility companies. Multi-Agent simulation of the transportation system containing such integrated multimodal public transportation system can give insightful information about the benefits such integrated system can bring to the entire society.

As we attempted to develop a multi-agent optimization model for the transit system case (Guo et al, 2016; Guo and Fan, 2017), we realized that a critically needed input piece was missing, which is the transit demand data. Therefore, we delved much effort into developing an estimation model to infer those missing data based on partial information of counting data automatically collected by transit agencies. The inference model shows some promise for a small-scale testing case, but more work is needed to explore its performance in a larger and more complicated transit network.

Overall, with private mobility services as a supplement to the existing transit system, there requires collective efforts from academia, service providers as well as transit users to explore more creative and effective ways of utilizing available mobility services to achieve a sustainable future transportation system. This one-year project is only a small attempt towards this goal. Much more system analysis and modeling efforts are needed to this end.

References

Chriqui, C. and Robillard, P. ,1975. Common bus lines. Transportation science, 9(2): 115–121.

Christopher W. Jenks, 2007. National Cooperative Highway Research Program Research Results Digest 319: “Buy America Issues Associated with the State DOT Procurement of Paratransit Vehicles Using FTA Funds”

Clugston, Laura, 2017. “A Winning Combination: Uber and Public Transit.” UBER Blog, UBER, www.uber.com/blog/seattle/a-winning-combination-uber-and-public- transit/.

Cunningham-Parmeter, K., 2016. From Amazon to Uber: Defining Employment in the Modern Economy. BUL Rev., 96, p.1673.

De Cea, J. and Fernández, E., 1993. Transit assignment for congested public transport systems: an equilibrium model. Transportation science, 27(2):133–147.

Daganzo, C. F., 2010, Public Transportation Systems: Basic Principles of System Design, Operations Planning and Real-Time Control, institute of transportation studies, University of California Barkley.

Dessouky, M., R. Hall, L. Zhang, A. Singh, 2003, Real time control of buses for schedule coordination at a terminal, Transportation Research, 37A.

Education, D.R. and Golden, M., 2014. Accessible Transit Services for All.

Enoch, M. and Potter, S., 2016. Paratransit: the need for a regulatory revolution in the light of institutional inertia. In Paratransit: Shaping the Flexible Transport Future (pp. 15-34). Emerald Group Publishing Limited.

Fan, Y. and C.Z. Liu, 2010. Solving Stochastic Transportation Network Protection Problem using the Progressive Hedging-Based Method, Networks and Spatial Economics, 10(2), pp. 192-208.

Fan, W., and Machemehl, R., 2006, “Optimal transit route network design problem with variable transit demand: A genetic algorithm approach.” J. Transp. Eng., 132, 1, 40–51.

Ferris, B., Watkins, K. and Borning, A., 2011, January. OneBusAway: Behavioral and satisfaction changes resulting from providing real-time arrival information for public transit. In Proceedings of the 2011 Transportation research board annual meeting.

Foxall, James. 2016 . “Is It Greener to Travel by Bus or by Car?” The Telegraph, Telegraph Media Group, www.telegraph.co.uk/cars/advice/is-it-greener-to-travel-by-bus-or-by-car/.

Giannopoulos, G., 1989, Bus Planning and Operation in Urban Areas: A Practical Guide.

Gooze, A., Watkins, K. and Borning, A., 2013. Benefits of real-time transit information and impacts of data accuracy on rider experience. Transportation Research Record: Journal of the Transportation Research Board, (2351), pp.95-103.

Golden, M., Chia, D., Ellis, B. and Thatcher, R., 2014. Accessible Transit Services for All (No. FTA Report No. 0081).

Guo, Z. and Y. Fan, 2017. A Stochastic Multi-agent Optimization Model for Energy Infrastructure Planning under Uncertainty in An Oligopolistic Market, Networks and Spatial Economics.

Guo, Z., J. Deride, Y. Fan, 2016. Infrastructure Planning for Fast Charging Stations in a Competitive Market, Transportation Research Part C, 68, pp. 215-227.

Harker, P. and J.S. Pang, 1990, Finite-dimensional variational inequality and nonlinear complementarity problems: A survey of theory, algorithms and applications, Mathematical Programming, 48, 161-220.

Jay Tyree, 2017, Memorandum on VTA Transit Ridership Decline subject, Santa Clara VTA

Lam, W. H.-K., Gao, Z., Chan, K., and Yang, H., 1999. A stochastic user equilibrium assignment model for congested transit networks. Transportation Research Part B: Methodological, 33(5):351–368

Liu, C.Z., Y. Fan, and F. Ordonez, A two-stage stochastic programming model for transportation network protection, Computers and Operations Research, 36(5), pp. 1582-1590, 2009.

Murphy, C., 2016, Shared Mobility and the Transformation of Public Transit, TCRP J- 11/TASK 21, https://www.apta.com/resources/reportsandpublications/Documents/APTA-Shared-Mobility.pdf (accessed on 3/27/2017).

Lowe, M., Aytekin, B. and Gereffi, G., 2009. Public transit buses: A green choice gets greener. Center on Globalization Governance and Competitiveness.

Murphy, C., 2016, Shared Mobility and the Transformation of Public Transit, TCRP J- 11/TASK 21, https://www.apta.com/resources/reportsandpublications/Documents/APTA-Shared-Mobility.pdf (accessed on 3/27/2017).

Nagurney, A., 2010. Supply chain network design under profit maximization and oligopolistic competition. Transportation Research Part E: Logistics and Transportation Review, Vol. 46, No. 3, pp. 281-294.

Neff, J. and Pham, L., 2007. A profile of public transportation passenger demographics and travel characteristics reported in on-board surveys.

Nelson\Nygaard Consulting Associates, TWJ Consulting, RLS and Associates, United States. Federal Transit Administration, Transit Cooperative Research Program and Transit Development

Corporation, 2007. Toolkit for Integrating Non-dedicated Vehicles in Paratransit Service (Vol. 121). Transportation Research Board.

Osuna, E.E. and G.F. Newell, 1972, Control strategies for an idealized public transport system, Transportation Science, Vol.6 (1).

Salzberg, Andrew, 2017. “Uber + Transit Makes It Easy to Be Multimodal.” UBER Newsroom, www.uber.com/newsroom/transitapp/.

Sinha, K. C., 2003, Sustainability and urban public transportation, J. Transp. Eng., 129, 4, 331–341.

TCRP., 1996, Transit Cooperative Research Program. Report 19, Guidelines for the Location and Design of Bus Stops. Transportation Research Board. National Academy Press. Washington, DC.

Windmiller, S., Hennessy, T. and Watkins, K., 2014. Accessibility of Communication Technology and the Rider Experience: Case Study of Saint Louis, Missouri, Metro. Transportation Research Record: Journal of the Transportation Research Board, (2415), pp.118-126.

Zhao, F., and Zeng, X., 2007, Optimization of user and operator cost for large scale transit networks, J. Transp. Eng., 133, 4, 240-251.