ACCESSING PUBLIC TRANSIT BY BIKE SHARING SYSTEM

A Thesis

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by

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ABSTRACT

The implementation of bike sharing systems is becoming popular in the cities around the world. Bike sharing systems could be one component of public transportation systems and has the potential to solve the last mile problem in public transportation. This study demonstrates the effects of implementing a bike sharing system into public transportation systems using continuum approximation method. The implementation of bike sharing system could have various effects on user cost, agency cost and greenhouse gas emissions depending on the profile of the city in question. This study shows that implementing bike sharing systems reduce users' opportunity cost in most cities except for small, sparsely populated, low-income cities. This study also indicates that implementing bike sharing systems sometimes increases transportation agency costs because of the additional facilities required for proper implementation. Effective policies are needed to bridge these funding gaps and realize the benefits of bike sharing for commuters in the city.

Keywords: bike sharing, trunk, feeder, last mile problem, greenhouse gas emissions.

BIOGRAPHICAL SKETCH

Jiayun Sun is currently finishing his second year of study in Civil and Environmental Engineering at Cornell University. In August 2017, he will graduate with a Master of Science degree in Transportation System Engineering.

Jiayun started his study in Environmental Science six years ago at Tongji University in Shanghai. With a strong interest in the study of transportation systems and encouragement from the professors and curriculum during his visiting year at University of California, Berkeley, Jiayun changed his major to transportation engineering and started pursuing a master's degree at Cornell University.

During his graduate years at Cornell University, Jiayun studied various aspects of transportation and urban development from the classes provided by a number of programs and departments including Civil and Environmental Engineering, City and Regional Planning, Cornell Program in Infrastructure Policy, and Dyson School of Applied Economics and Management.

Outside of academics, Jiayun enjoys exploring Ithaca's natural environment and is involved in many outdoor activities in upstate New York. He learned snowboarding at Greek Peak and cannoning at Cayuga Lake with instructors from Cornell Outdoor Education and always hiked to visit beautiful sites around Ithaca.

This thesis is dedicated to my parents

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CHAPTER 1

INTRODUCTION AND LITERATURE REVIEW

Bike sharing is the shared used of a bike fleet and is a transport method that is becoming increasingly popular around the world. With the increasing concerns about the impacts of fossil-fueled cars and efforts to rejuvenate urban walkable areas, bike sharing systems garner support across cities in both developing countries and developed countries. In the United States, the first modern bike sharing systems started operating about five years ago in Denver, Washington, D.C., and the Twin Cities to ease congestion, decrease air pollution and add fun to city life. Today, 119 cities have bike sharing systems in the United States (Malouff, 2017).

Bike sharing systems are attractive to younger generations (Buck, et al., 2013) and intuitively encourages better design for public spaces. These flexible systems, which don't require users to own bicycles, have the potential to replace automobiles for some short distance travel and also promote accessibility of public transit. Thus, bike sharing systems are an appealing solution for last-mile problem in transportation systems.

The first bike sharing system with stations, established in 1996, was named Bikeabout. Bikeabout was a small bike sharing system for students at Portsmouth University in the United Kingdom (CityLab, n.d.). Subsequently, many other schools also started their own campus bike sharing systems. Today, the ultimate goal of bike sharing is to integrate cycling into transportation systems (Shaheen, Guzman, & Zhang, 2010). Although there are growing trends in using bike sharing systems, these systems are not always successful. Seattle launched a bike sharing system, Pronto, in October 2014 but system stopped operating in March 2017. Reasons for the termination were said to be low ridership, delayed expansion, funding gaps and political issues (Small, 2017). Public transportations do not make profits in most cases and always require public subsidies. The value of public transportation is mostly reflected in its social benefits and the promotion of agglomeration economies. Bike sharing systems have failed to be sustainable in some cities because these bike sharing systems were not treated as part of public transportation networks and because they operated separately from public transit systems. Since systematic studies have not been conducted on the effects of bike sharing systems on the urban transportation systems, it is necessary to approach the implementation of bike sharing from a systematic perspective.

Some efforts have been made to promote the integration of bike sharing into public transit systems. In Helsinki, the bike sharing system is said to link seamlessly with the metropolitan area's multi-modal public transportation system. All modes of public transportation include bike sharing are included in the region’s transit Journey Planner. Users can also pay all trip fares using one smartcard called Helsinki Travel Card (City of Helsinki, 2016). In the United States, members of House Representatives introduced the Bikeshare Transit Act to officially designate bike sharing as a mode of public transportation. This Act could have a positive effect on filling funding gaps for bike sharing through the utilization of federal funds (Kinney, 2016). This thesis attempts to provide numerical evidence that integrating bike sharing into public transit systems could have benefit for users, transportation agencies, and environment. Some comparisons and enumeration of costs using a proposed trunk-feeder system model will give insights into the feasibility of bike sharing systems in cities of different sizes and trip generation rates.

1.1 Competitive Transit Networks

Originally proposed by Daganzo (2010), the structure of the competitive transit network model is designed to deliver an accessibility level comparable automobiles (Daganzo, 2010). The model was then used to compare the performance of different transportation technologies. An explicit trunk-feeder system was proposed and the results suggested that faster access links, such as cycling, to trunk systems could promote the use of fast and high-volume trunk transportation technology (Sivakumaran, Li, Cassidy, & Madanat, 2014). Sivakumaran's work discussed using bikes as feeder systems but the only parameter changed from a walking scenario was access speed. Sivakumaran's study did not consider the integration of bike sharing systems and the increased agency cost as a result of additional bike sharing facilities. In this thesis, I use a structure similar to the trunk-feeder model and insert bike sharing components to reflect the tradeoff between user costs and agency costs. The coefficients for bike sharing systems in the cost function have been derived based on other studies (Sivakumaran, Li, Cassidy, & Madanat, 2014) (Zhang, Zhang, Duan, & Bryded, 2015), reports (Arizona Bike Law, 2010) (Bushell, Poole, Zegeer, & Rodriguez, 2013) (Kurtzleben, 2012) (Roth, 2011) (Tencent Technology News) (Toole Design Group, LLC and Foursquare ITP, 2013) and industrial standards (Landa, 2014) (NACTO, n.d.).

1.2 Reduction in Greenhouse Gas (GHG) Emissions

A 2013 study analyzing the impact of transit systems on emissions, suggested that a variety of trunk technologies can be applied in different cities to achieve the greatest reduction in GHG emissions (Griswold, Madanat, & Horvath, 2013). In the study, the authors presented a strategic framework for incorporating GHG emissions into transit planning decisions. Griswold suggested in another study that optimizing urban bus transit network design can lead to a reduction in GHG emissions (Griswold, Sztainer, Lee, Madanat, & Horvath, 2017). Both of these studies utilized a framework of continuum approximation optimization models, which meant that their GHG emissions model could be easily adapted to the analysis of GHG emissions when using bike sharing as a feeder system. Intuitively, researchers would think that bike sharing systems have low GHG emissions because riding bikes does not burn fossil fuel. However, an article has highlighted that there is no robust evidence that bike sharing systems serve as substitutes for more energy-intensive ways of moving around cities. The nascent academic literature on bike sharing systems tends to examine trip patterns in isolation from wider urban transport systems (Schwanen, 2014). Regarding the lack of life cycle GHG emissions for bike sharing systems, this thesis makes inference and reference to studies on conventional bike facilities (Griswold, Madanat, & Horvath, 2013) (Matute, 2016) to propose a structure for analyzing the GHG emissions of bike sharing systems integrated into larger public transit networks.

1.3 Planning Framework

As previously discussed, public transit and city GHG emissions performance could benefit from the implementation of bike sharing systems, however this implementation is difficult and strategic planning for bike sharing systems is often not considered from a system perspective. Some feasibility studies on the implementation of bike sharing systems are based on the experiences of other cities (Toole Design Group, LLC and Foursquare ITP, 2013) (Toole Design Group, 2014). These strategic plans always focus on the operational performance and funding mechanism of the bike sharing programs. Filling funding gaps by reducing operations or delaying expansion may decrease the utility of bike sharing systems (Small, 2017). Evidence presented in prior studies suggests that planning bike share system connectivity with public transit networks should be addressed with system-level policies. This is because there is a strong link between strategic planning and measurable implementation. A nuanced, highly-local approach to station placement and network improvement is needed in planning bike sharing systems (Griffin & Sener, 2016). A proposed policy framework outlined in Griffin and Sener's study suggests the need for numerical analysis of bike sharing systems from a transit system perspective. This thesis aims at numerically modeling the effects of introducing bike sharing on transit user costs, transit agency costs and GHG emissions from a public transit system perspective.

This thesis will present the structure of a trunk-feeder model with bike sharing as feeder system in Chapter 2. Based on this model, Chapter 3 presents the numerical experiments used to evaluate the effects of implementing bike sharing systems in cities of different sizes and trip densities. Chapter 4 discusses GHG emissions and presents case studies on policy regarding the implementation of bike sharing systems in Seattle, Los Angeles and Shanghai. Chapter 5 concludes by discussing the effects of implementing bike sharing systems and provides suggestions on future avenues for study.

CHAPTER 2

TRUNK-FEEDER SYSTEM MODEL

Table 1 List of notations

Urban morphologic parameters	
l [km]	length and width of the city
ρ [trips/km^2-hr]	trip generation rate
λ [trips/hr]	overall demand generation rate, $\lambda = \rho l^2$
v_a [km/hr]	walking speed
ω [$/hr]	average income of citizen
Operating parameters	
t_r [secs]	transfer time from one line to another
τ [secs]	dwell time at each station
v_t, v_f [km/hr]	trunk vehicle cruising speed, bike riding speed
K [pax/veh]	passenger capacity
Q [veh/hr]	line capacity
b [bikes/station]	number of bikes at each station
Cost parameters	
π_{IL}, β_{Il} [$/km-hr]	coefficient of line infrastructure cost
π_{IS}, β_{Is} [$/station-hr]	coefficient of station infrastructure
β_{Ir} [$/rack-hr]	coefficient of bike rack cost
π_M, β_M [$/veh-hr]	coefficient of time dependent operating cost
π_V, β_V [$/veh-km]	coefficient of distance dependent operating cost
Decision variables	
s [km]	average distance between trunk system stations
p	number of sections between two transferable trunk stations
r [km]	trunk system line space, $r = ps$
H [min]	headway of trunk operation
s_f [km]	average distance between feeder (bike sharing) system stations

The trunk-feeder system model was proposed to integrate public transit as trunk systems with bike sharing as feeder systems. The skeleton of the model is the trunk system, which could be a bus system, bus-rapid-transit (BRT) system or rail system. People can access trunk stations by walking or via a feeder system. This chapter discusses the structure of a proposed model for trunk only systems and trunk-bike sharing systems.

The objective of the model is to minimize user costs and agency costs at the same time. User cost is the average cost for commuters accessing, waiting at and riding in the transit system. Agency cost consist of the investments made in line construction, stations, rolling stock and maintenance that make up a public transit system. All costs are weighted and converted into dollars based on estimated coefficients, which are sorted by high-income cities ($20/hour) or low-income cities ($3/hour). The decision variables within the model are the distance between trunk stations, the distance between trunk lines, the headway of trunk lines, and the distance between feeder stations (bike-sharing stations). The proposed model is evaluated under different scenarios, which are defined by the size, trip density, and income level of the cities. The formula utilized will be explained explicitly in this chapter.

2.1 Formula for Accessing Trunk System by Walking

The cost function and trunk-feeder system are extracted from the model of a trunk-feeder transit system (Daganzo, 2010) (Sivakumaran, Li, Cassidy, & Madanat, 2014). The model assumes that people are traveling in a square city with length L [km]. The origins and destinations are uniformly and independently distributed within the city area L^2 with a trip generation rate ρ [trips/km^2-hr]. The trunk system would be laid parallel to the grid street within the city. Stations on the trunk system are apart with a distance of s [km]. Trunk lines are apart from each other by a distance of

r [km], where $r = ps$. The p here represents the sections between two transfer stations, or (p-1) non-transfer station between two transfer stations. Figure 1 gives an example of such grid trunk system where $p = 2$.

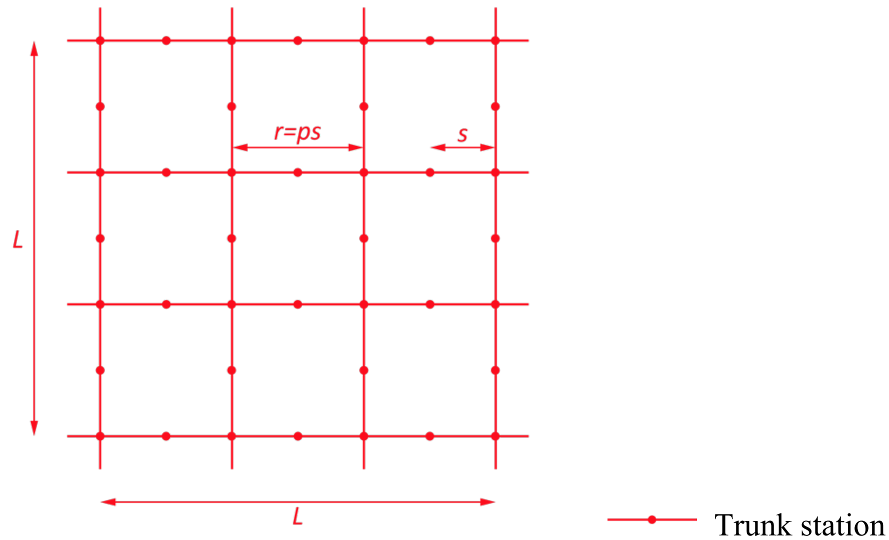

Fig. 1 The layout of trunk lines and stations

The costs of a trunk only system includes user costs and agency costs. User cost includes three elements, access time A, waiting time at the trunk station Y and riding time on trunk line T. The distance between two points is calculated in Manhattan distance within the model. The average access time is the average travel time divided by the average speed to access the station. In this case, the access speed is walking speed (2 km/hr). The access speed would change when integrating feeder systems into transit networks. The average waiting time Y at trunk station is the sum of headway H and transfer time. This model assumes that people transfer once within the system. The average riding time T consists of the expected travel time and dwell time at stations. These times are then converted into dollars based upon the income level of a given city. For agency costs, the coefficient would also vary for cities with given different income levels. The values of these coefficients are presented at the Data Feeding section of next chapter.

User Costs

$A = (1+p)\frac{s}{2v_a}$ Average access time to a trunk station

$Y = H + t_r$ Average waiting time at trunk station

$T = \frac{2L}{3v_t} + \frac{2L\tau}{3s}$ Expected travel time in transit

Agency Costs

$I_l = \frac{2L^2}{ps}$ Cost to construct trunk system alignment

$I_s = \frac{I_l}{s} = \frac{2L^2}{ps^2}$ Cost of building stations for trunk system

$V = \frac{2I_l}{H} = \frac{4L^2}{psH}$ This term represents the distance dependent operation and maintenance cost. Coefficients are concluded from the energy consumption and maintenance cost.

$\frac{1}{v_c} = \frac{1}{v_t} + \frac{\tau}{s}$ The pace of vehicles, this formula is used in calculating M

$M = \frac{V}{v_c} = \frac{4L^2}{v_t psH} + \frac{4L^2\tau}{ps^2H}$ This term is the time dependent operation and maintenance cost, which considers labor costs and the depreciation of vehicles.

The objective of this function is to minimize the sum of the formulas given above. The value of the objective function is the generalized total cost for a commuter using the transportation system.

Objective Function,

$$z(p,s,H) = \omega A + \omega Y + \omega T + \pi_{Il} I_l + \pi_{Is} I_s + \pi_V V + \pi_M M$$

subject to

$\frac{1}{4}\rho LpsH \le K_t \left[\frac{pax}{hr}\right]$ The volume of riders should not exceed the capacity of trunk line. Or the trunk line should be designed to meet the trip demand of the city.

$ps \leq \frac{L}{2}$ There are at least two transit lines in each direction to comprise the system.

$H^{-1} \leq Q_t[\frac{veh}{hr}]$ The headway of the trunk system is limited to the line capacity.

2.2 Formula for An Integrated Network with Trunk System and Bike Sharing System

This section discusses the integration of a trunk system utilizing bike sharing as a feeder system. Intuitively, using bikes as a feeder system makes access to trunk stations easier and faster as compared to walking. However, the construction of bike sharing systems incur additional infrastructure costs. On the other hand, the implementation of bike sharing systems could lower density within trunk systems and reduce the infrastructure cost of trunk systems. The overall effect of this proposed model is analyzed using a numerical experiment in next chapter.

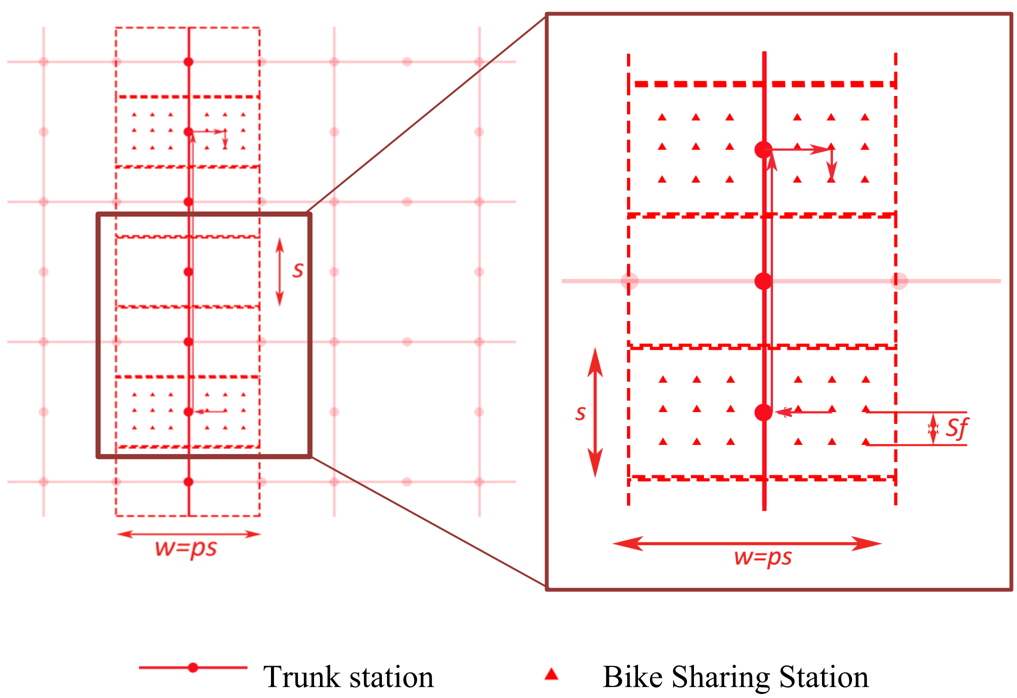

Fig. 2 Layout of trunk system and integrated bike sharing system

As depicted in Figure 2, bike sharing stations are uniformly distributed in the catchment area of each trunk station. The average distance between bike stations is s_f. Each bike station has b bikes. The number of racks depends on the bike/rack ratio, which is set to 1.75, based on recommendations found in a public bike feasibility study (Quay Communications Inc, 2008). A typical commuter in a model system will start their journey by bike and transfer to a trunk line system, then use a bike again for the last segment of his or her destination. In addition to the parameters of a trunk only system, this mixed system contains more parameters specifically reflecting the operation of a bike sharing system. The additional parameters include the number of bikes (racks) in each station b and the speed of biking v_f. The elements of user cost and agency cost have also been modified to fit the mixed system which uses bike sharing as a feeder technology.

User Costs

$A_f = \frac{s_f}{2v_a}$ Average time to access a bike station.

$Y_f = H + t_r + 2t_{f-t}$ Transfer time between trunk lines and from bikes to trunk lines.

$T_f = \frac{2L}{3v_t} + \frac{2L\tau}{3s} + \frac{(p+1)s}{2v_f}$ Expected riding time on trunk system and feeder system

Agency costs

$$\pi(I_{fl}) = \pi_{Il}\frac{2L^2}{ps} + \beta_{Il}\frac{2L^2}{s_f}$$

This term represents the construction costs of trunk lines and bike lanes for bike sharing system. Dedicated bike lanes are important for the safety of the riders (Gu, Mohit, & Muennig, 2016) and bike lanes are important for the feeder system to achieve designed cruising speed.

$$\pi(I_{fs}) = \pi_{Is}\frac{2L^2}{ps^2} + (\beta_{Is} + \beta_{Ir} * 1.75\ b)\left(\frac{L^2}{s_f^2} + \frac{L^2}{ps^2}\right)$$

This term represents the construction cost for trunk stations and feeder bike stations. The construction costs for trunk station remains the same, while the cost of bike sharing stations consists of station cost and rack cost. The number of racks would be determined by the number of bikes required at each station.

$$\pi(V) = \pi_V\frac{4L^2}{psH} + \beta_V\frac{(p+1)bsL^2}{2}\left(\frac{1}{s_f^2} + \frac{1}{ps^2}\right)$$

This term similarly represents the distance dependent operation and maintenance cost of a mixed system. Coefficients are concluded from the energy consumption and maintenance cost.

$$\pi(M) = \pi_M\left(\frac{4L^2}{v_t psH} + \frac{4L^2\tau}{ps^2H}\right) + \beta_M bL^2\left(\frac{1}{s_f^2} + \frac{1}{ps^2}\right)$$

This term is the time dependent operation and maintenance cost, which considers labor costs and the depreciation of vehicles.

The objective function for this mixed system is similar to the function for a trunk only system. Total cost is the sum of user costs and agency costs.

Objective function,

$$z(p,s,H,Sf) = \omega A + \omega Y + \omega T + \pi(I_{fl}) + \pi(I_{fs}) + \pi(V) + \pi(M)$$

subject to

$\frac{1}{4}\rho LpsH \le K_t\ \left[\frac{pax}{hr}\right]$ The volume of riders should not exceed the capacity of trunk line. Or the trunk line should be designed to meet the trip demand of the city.

$ps \le \frac{L}{2}$ There are at least two lines in each direction to comprise the system.

$H^{-1} \le Q_t[\frac{veh}{hr}]$ The headway of the trunk system is limited to the line capacity.

$\rho S f^2 \leq \eta Q_f [\frac{veh}{hr}]$

The feeder system should meet the trip demand. Bike availability should exceed the η of total demand. Some reports conclude that in cities like Shanghai, 50%-60% people use bike sharing systems to transfer to subways and commute (Mobike and Tongheng Urban Data Lab, 2017).

$\frac{(p+1)s}{v_f} \leq 1$

Most systems allow users to ride for 30 minutes before charging additional fees. The 30-minutes limit applies to both approaching and leaving the trunk system. The total cycling time is limited to 1 hour.

$\frac{b * p * s^2}{s_f^3} \leq \frac{Q_f}{v_f}$

The most used bike lanes in the system would not exceed its capacity.

$2s_f \leq ps$

There are at least two bike stations between trunk lines to make up the system.

2.3 Assumptions

There are some assumptions that need to be discussed here. While some of these assumptions may not closely mirror reality, these assumptions are used in order to create the model and better serve the purpose of the model.

Spatial and time uniformity: Assumes that trip origins and destinations are uniformly distributed within the study area, we could have a trip generate rate of the area. This model also assumed that the trip generation rate is uniform throughout the day. This is different from reality because urban land use and density is not uniformly distributed. Also, commuting occurs in patterns, which generates rush hours in the morning and evening. The assumed spatial and time uniformity makes the model stochastic. The goal of the model is to describe the optimal structure of the city's public transportation system and serve as a reference for transportation infrastructure planning. Ideally, heterogeneity in trip demand should also be considered but this variable would make the model much more complex and beyond the scope of this analysis. Therefore, the model assumes uniformly distributed trip generation.

No repositioning cost for bike sharing system: This assumption results from the spatial and time uniformity in the model. In reality, bike fleets within a bike sharing system will cluster in some places, leaving some stations empty during service hours. Trucks or other carriers are needed to reposition bikes from stations with excess bikes to nearly empty stations. This repositioning sometimes leads to high operation costs for bike sharing systems (Schuijbroek, Hampshire, & Hampshire, 2013). In this model, the origins and destinations of the trip are uniformly distributed. In the morning, bikes brought to the trunk stations by commuters living in the catchment area will be rode out of trunk stations by commuters working in the same catchment area. Thus, the fleet will rebalance itself if the trips are uniform. Although this assumption is not the real case, it fit the design of the model. And the potential repositioning cost could be integrated into the coefficients of the operating and maintenance costs.

CHAPTER 3

NUMERICAL EXPERIMENT

With different cultural backgrounds and level of economic development, cities as settlements have distinct morphologic characters. Some of the important parameters of cities are size and population of the city. These two parameters affect the scale of agglomeration economies within the city. With increasing numbers of people moving into cities, transportation facilities must now sustain higher pressure than ever before. Most cities in developed countries have mature public transportation systems, these facilities are aging and have high maintenance cost. Meanwhile, cities in developing countries are growing fast and some of these cities are suffering from the diseconomies caused by insufficient transportation facilities.

Introducing bike sharing systems into the urban area is popular around the world. There are 1188 cities around the world operating their bike sharing systems (Meddin, 2017). Some of those cities are big and dense, such as Paris or New York. Some are small and less dense, such as Boulder in Colorado. A scatter plot of the cities by their size and population density indicates that the city sizes range up to around 50 km (in length, assume cities are square) and that the population densities range from very small to about 500,000 people/km^2. City sizes and population densities are scattered and seem independent from each other.

This chapter focuses on a numerical experiment with some hypothetical cities and the trunk-feeder model proposed in last chapter. These hypothetical cities range from 10km to 50km in length. The trip generation rates range from 50 trips/km^2-hr to 500 trips/km^2-hr. In addition to the size and trip generation rates of these cities, the income levels are also considered. Cities are categorized into low-income cities ($3/hr) and high-income cities ($20/hr), representing cities in developing countries and developed countries.

Comparisons are made between cities of different levels of income and the implementation of bike sharing system. The results are presented as heat maps of optimal modes, generalized costs and percentage changes after implementing bike sharing system.

The optimization method is mixed nonlinear optimization. The optimization mixes integer variables (the choice of transportation technology and value of p) with continuous variables. This makes the result discontinuous. Some of the outliers have been tested with genetic programming, which could avoid the results being trapped into wrong local minimum. Genetic programming can help avoid the wrong local minimum at some points but it would not provide the accurate optimal value (Boyd, Kim, Vanderbeghe, & Hassibi, 2007). The following results of numerical experiment utilize the nonlinear optimization method.

3.1 Hypothesis

The results are expected to indicate the feasibility of bike sharing systems in cities with different sizes and trip densities. In other words, what kind of city could have the most reduction in generalized costs from the introduction of bike sharing systems? Prior research showed that faster access to trunk systems, like cycling, could reduce generalized costs (Sivakumaran, Li, Cassidy, & Madanat, 2014). However, the research did not include the cost of the bike sharing facilities. In this thesis, I further include expenses on bike sharing facilities, which could increase agency costs. A reduction of generalized cost is expected for most cities but the agency costs could increase due to the need for additional facilities. This tradeoff between user cost and agency cost is expected to be evaluated in the numerical experiment.

3.2 Data Feeding

The parameters of a trunk only system are referenced in the study by Sivakumaran (2014). The parameters of a bike sharing system are estimated following the logic of Sivakumaran's study. This estimation makes the model consistent. The explicit estimation process and sources of bike sharing parameters is found in Appendix B, C and D.

Table 2 Transit technology parameters

	Time per Transfer t_r [seconds]	Lost Time per Station τ [seconds]	Cruising Speed v_t [miles/hr]	Passenger Capacity K [pax]	Line Capacity Q_{max} [Vehicles/hr]
Bus	10	30	25	80	20
BRT	20	30	40	120	30
Rail	60	45	60	1000	15
Bike	20	0	12	1	3800

Table 3 Cost parameters for low-income city

	Infrastructure Cost – Lines C_{IL} [$/km-hr]	Infrastructure Cost – Stations C_{IS} [$/station-hr]	Operating Cost – Fleet Size C_M [$/veh-hr]	Operating Cost – Distance C_V [$/veh-km]
Bus	7	0.49	21	0.59
BRT	190	4.9	28	0.66
Rail	690	340	130	2.2
Bike	17.54	0.43 (station) 0.01 (rack)	0.05	0.1

Table 4 Cost parameters for high-income city

	Infrastructure Cost – Lines C_{IL} [$/km-hr]	Infrastructure Cost – Stations C_{IS} [$/station-hr]	Operating Cost – Fleet Size C_M [$/veh-hr]	Operating Cost – Distance C_V [$/veh-km]
Bus	10	0.7	63	0.59
BRT	270	7	84	0.66
Rail	990	490	200	2.2
Bike	22.26	0.84 (station) 0.01 (rack)	0.17	0.1

3.3 Result 1, Optimal Choice of Transit Technology

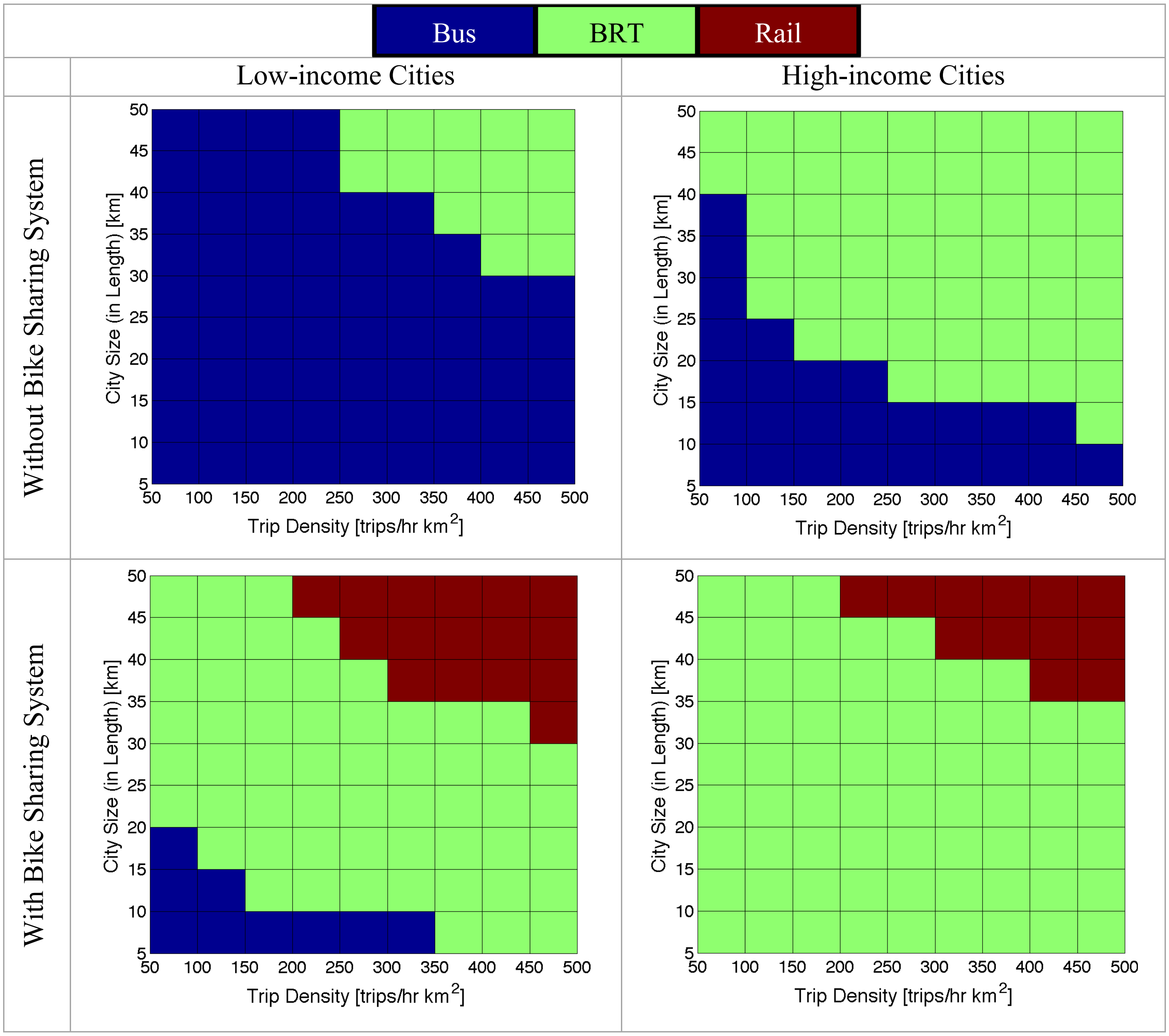

Fig. 3 Optimal mode for trunk system

High income cities have a preference on mass transit. In the cases where commuters access the trunk system by walking, the matrixes for transportation modes indicate that BRT is more competitive than buses in high-income cities than compared to low-income cities. This is reasonable because high-income citizens have a higher value of time and could invest more in transportation infrastructure to reduce their commuting time. Another observation is that rail is not the optimal choice for both low and high-income cities. In reality, many big or densely populated cities choose rail system as their trunk transportation technology. The advantages of rail systems or other mass transit systems could exceed the scope of this model. The strong Mohring economies of subway systems encourages the use of transit systems, which further helps to realize the benefits of subway systems (O'Sullivan, 2012). This model includes the concept of accessibility and infrastructure expenses, but does not capture other social benefit. Using this simplified model, the results still indicate that high-income cities have a tendency to use fast, high-capacity transportation technology.

Bike sharing systems could encourage the use of faster and higher-volume transportation modes. Introducing bike sharing systems reduces the use of buses as the optimal transportation technology and promotes the use of BRT and rail systems. It is interesting to observe that bike sharing systems can better help low-income cities adapt rail systems as compared to high-income cities. By comparing the changes in user cost matrixes and agency cost matrixes, I found this result could be derived from differing use of rail systems. In low-income cities, rail systems tend to be commuter rail systems rather than subway systems. Commuter rail system have longer distances between stations and lines. The commuter rail system is sparser than subway system. Thus, the infrastructure cost of commuter rail is lower than the costs for subway systems but the user cost saving is not as much as those of subway systems. In high-income cities, rail systems have small distances between stations and lines. These kinds of rail systems are more likely to be subway systems in metro area. A dense rail system could help reduce user costs but could also result in higher facility costs. These statements could conclude from the model output. The average value of s, distance between stations, for low-income cities when adopting rail system is about 3.1 km. The value for high-income cities is about 2.4 km. And the average value of r, distance between trunk lines, is 4.3 km for low-income cities and 2.4 km for high-income cities. This differing use of rail systems makes rail systems cheaper and more competitive in low-income cities.

Another study indicated that one of the potential benefit from bike sharing is increased use of public transit and alternative modes (Shaheen, Guzman, & Zhang, Bikesharing in Europe, the Americas, and Asia Past, Present, and Future, 2010). This result further points out that bike sharing systems could help to improve the feasibility alternative modes, such as BRT and rail development. A BRT or rail project would be better advocated for and utilized if it is carried out in conjunction with a bike sharing program.

3.4 Result 2, Generalized Cost Comparison

In Figure 4, these four cost matrixes represent generalized costs for different cities. The generalized cost includes user costs and agency costs. Generalized cost is not directly comparable for low-income cities and high-income cities because the colors are in different scales. The opportunity costs in high-income city are so high that makes the user cost more than tripled in high-income cities. However, the trends are the same.

Large, sparsely populated cities have the highest generalized costs. Small, densely populated cities have the lowest generalized costs. Infrastructure investment could be better utilized in small, densely populated cities. Thus, small, densely populated urban areas are suitable locations for promoting public transit. This is consistent with the relationship between public transit and high-density land use that transit and high density living can be mutually supportive (Smith, 1984). Secondly, implementing bike sharing systems could reduce generalized costs in some cities. To give explanation of the effects or changes in generalized cost, a comparison between costs before and after implementing a bike sharing system will be discussed in following section.

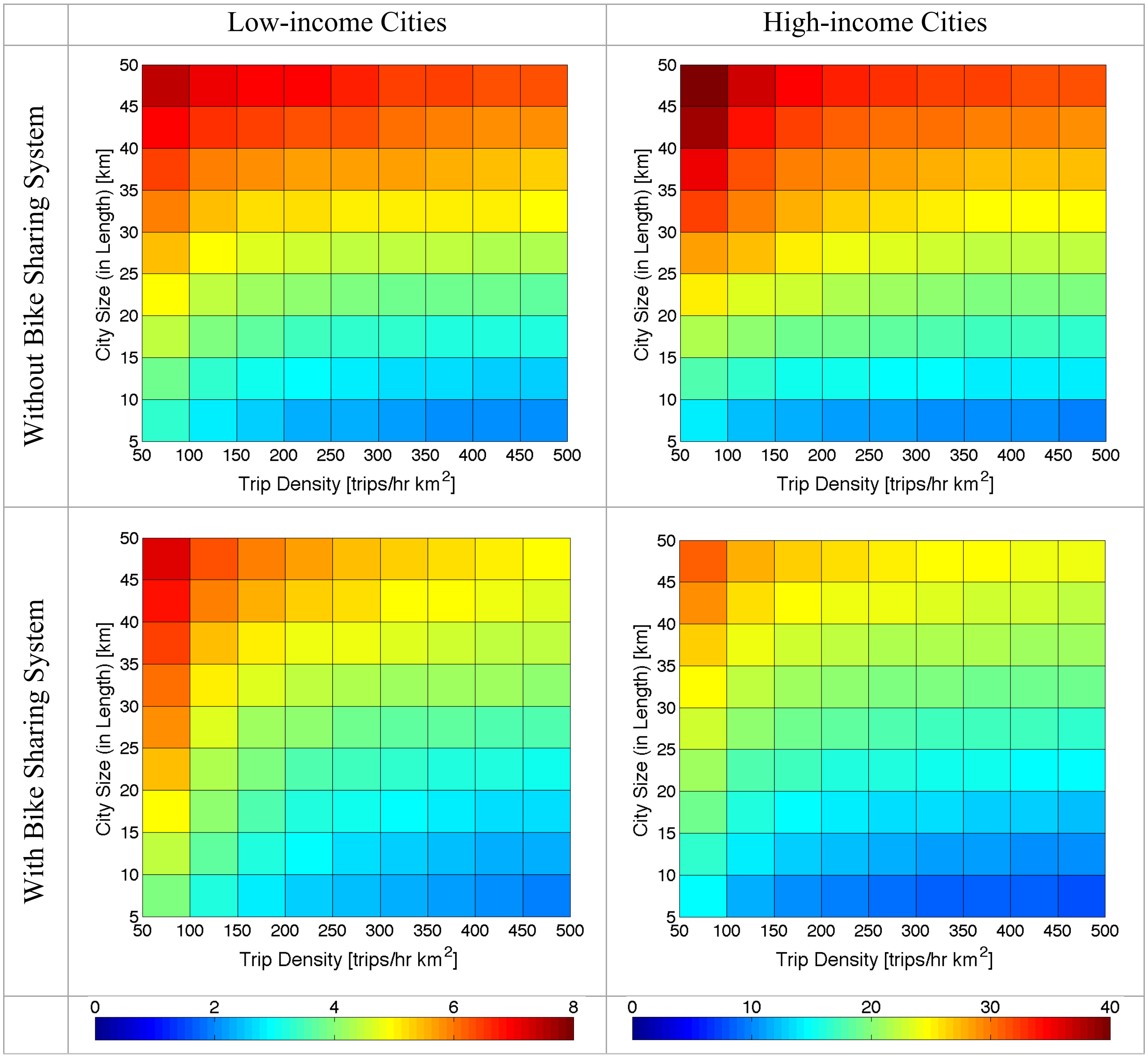

Fig. 4 Generalized cost of transportation systems

3.5 Result 3, Percentage Change after Implementing Bike Sharing System

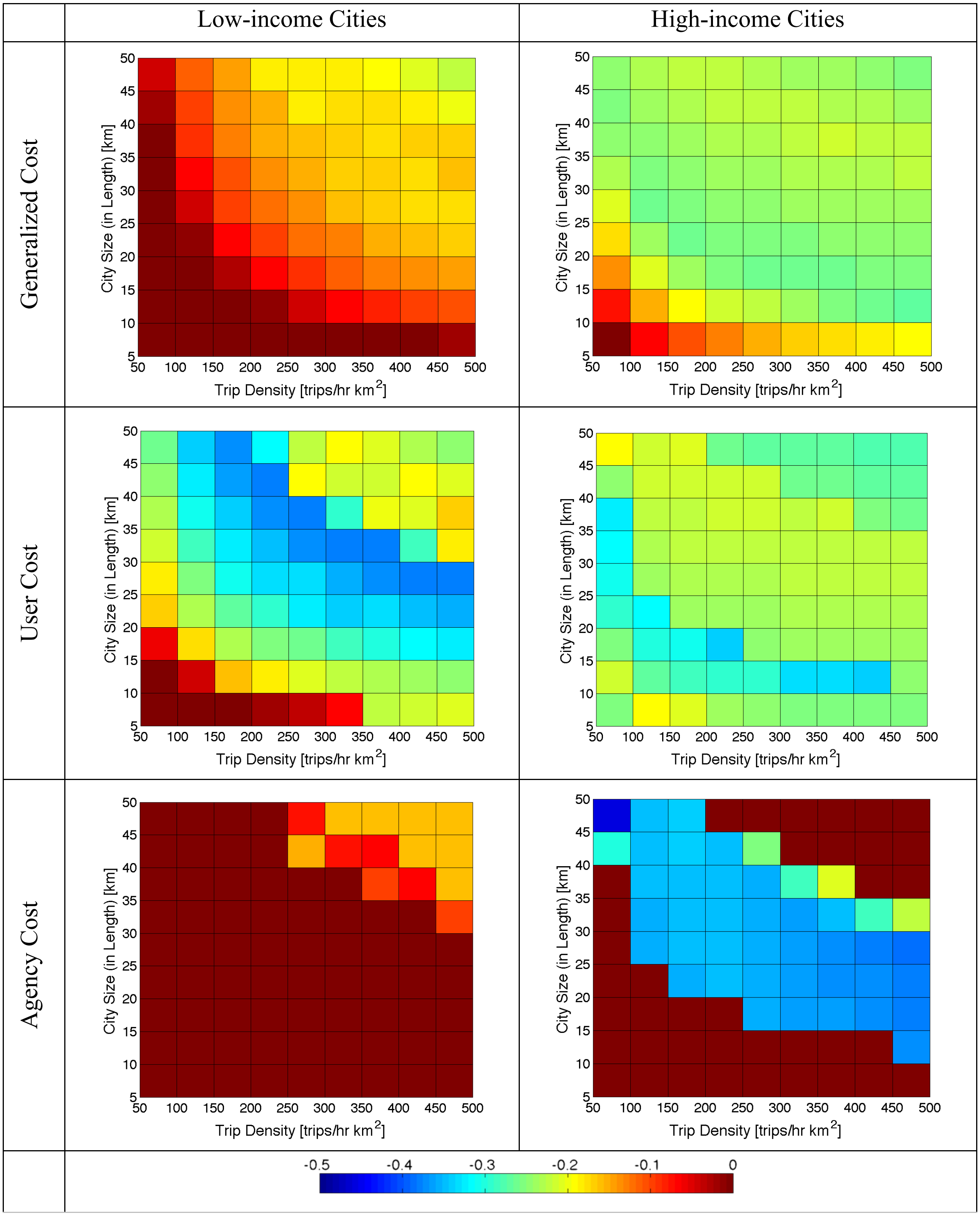

Fig. 5 Percentage changes after implementing bike sharing system

In Figure 5, the comparison heat maps indicate the percentage differences between implementing a bike sharing system and a trunk only system. The matrixes of generalized cost have similar patterns for both low and high-income cities. Introducing bike sharing has a better effect on reducing generalized cost for big and densely populated cities. It is not practical to implement bike sharing in very small or sparsely populated cities. For small or sparsely populated low-income cities, the introduction of a bike sharing system could make the generalized costs higher than the those of a trunk only scenario. For low-income cities that are small (size < 100 km^2 and trip density < 350 trips/km^2-hr) or sparse (size < 25 km^2 and trip density < 100 trips/km^2-hr), introducing bike sharing would increase both generalized costs and agency costs. In extreme cases where cities are very small and sparse, user costs also increase. Introducing bike sharing could reduce generalized costs except for the very small and sparse cities (size < 100 km^2 and trip density < 100 trips/km^2-hr). The reductions in generalized cost was around 25% for most cities. The reduction in generalized cost could be a tradeoff between user cost and agency cost. This is because some cities spend more on infrastructure in order to reduce the travel time for transit system users.

The results of this numerical experiment seem to suggest that small and sparse cities are not the best candidates for bike sharing systems. Bike sharing systems increased generalized costs for these types of cities. Nevertheless, there are some successful bike sharing programs in small cities (Christensen, 2013). By reviewing these programs, I found that most programs are in college towns. For example, the Madison B-Cycle covers the University of Wisconsin-Madison. Chattanooga Bicycle Transit System covers the University of Tennessee at Chattanooga. Boulder B-Cycle operates in and around the University of Colorado Boulder. Cornell University also operates a bike sharing system and the system mainly serves the campus and it is not designed to integrate with Tompkins Consolidated Area Transit (TCAT), the regional bus service. The reason for launching bike sharing systems in college towns could be that these bike sharing users are more likely to be younger (Buck, et al., 2013). The model discussed in this thesis is designed to make the bike sharing system serve the trunk public transportation system. The scenario where people solely use the bike sharing system is considered but not captured in the cost function. This group of users is a key factor that contributes to the success of bike sharing systems in small cities.

Table 5 Bike sharing systems in small cities (Christensen, 2013)

Program	Number of Stations	Fleet Size (bikes)	City Population	Estimate City Size (in length [km])	Estimate Trip Density [trips/km^2-hr]
Madison B-Cycle	35	225	240,323	15	50
Chattanooga Bicycle Transit System	32	300	171,279	20	<50
Boulder B-Cycle	22	150	97,385	10	50

3.6 Summary

Introducing bike sharing as a feeder system encourages the use of fast, high-volume transit technology in trunk systems, but does not necessarily decrease generalized costs. Introducing bike sharing systems can increase agency costs in some cases because of the additional facilities required in order to implement bike sharing systems, however these systems lower user costs. In small or sparsely populated cities, implementing bike sharing is not economically efficient. High-income cities realize greater benefits from the introduction of bike sharing systems as compared to low-income cities.

CHAPTER 4

DISCUSSION

4.1 Case Study

This discussion will be based on three cities, Seattle, Los Angeles and Shanghai. These cities are representative of some the distinct cities in the world. Seattle and Los Angeles are both high-income cities in a developed country and both have a history of around 150 years of modern development. Seattle launched its bike sharing system in October 2014 and terminated the system in April 2017. The termination of the system was due to low ridership, delayed expansion, lack of funding and political issues according to an article in *The Atlantic* (Small, 2017). It is interesting to analyze whether cities such as Seattle are inherently not suited for bike sharing systems or whether there is a way to integrate bike sharing into Seattle's existing transit system and help enhance the performance of the system.

Los Angeles is famous for its large urban area and low density neighborhoods. Los Angeles is also famous for its car culture. Los Angeles is a city that loves to drive. Almost 72% workers in Los Angeles commute by driving alone and only 7% use public transportation. The numbers for New York are 25% by car and 55% by public transit (Ramos, 2008). Los Angeles has an ambitious plan to expand public transportation in order to help battle the congestion facing the city. It is interesting to consider how bike sharing could possibly play a role in this expansion.

Shanghai is one of the most rapidly urbanizing areas among developing countries. Congestion has become increasingly problematic in the recent few years. Local government has issued several regulations to control the growth of car ownership and has also taken steps to promote public transportation. A dock-less bike sharing system was implemented last year and has dramatically changed commuting patterns. According to a report by Tsinghua University, 51% of bike sharing system users make transfers to the subway system and 90% users transfer to buses to finish their trips (Mobike and Tongheng Urban Data Lab, 2017). Some regulatory issues around bike sharing have emerged, posing challenges in the use of public space and for the sustainability of the bike sharing system. The following case study addresses the effects of station-less bike sharing systems and examines policies intended to regulate these systems, thereby enabling them to better work with existing public transit networks and future transit plans.

Overview of Trunk System of Study Cities

Seattle: Two public transportation agencies serve the city of Seattle, King County Metro Transit and Sound Transit. King County Metro's fleet mainly consists with buses and trolleys. Sound Transit provides express bus, light rail transit and commuter rail in the Seattle metropolitan area (Wikipedia: Transportation in Seattle). The light rail system was analyzed as the trunk system in this case. The distance between stations, number of sections between transfer stations and headways have been acquired from the website of Sound Transit.

Los Angeles: The city has a metro rail system servicing downtown Los Angeles and surrounding areas. The system has 6 lines and 93 stations. 1.1% of the 29 million daily trips use the metro rail system. Although the system ranks 6^{th} in the United States for the number of passengers per mile, the system only covers a very limited part of the city. Los Angeles' high rank for number of passengers per mile implies a high need for public transit. On November 9, 2016, Los Angeles Metro's transportation ballot measure (Measure M) was passed. Measure M is aimed at expanding the rail and rapid transit system in Los Angeles (Los Angeles County MTA, 2017). There are numerous proposals for future rail development. The metro rail system is analyzed in this chapter as an example of a densifying urban area, which deals with the excessive use of automobiles.

Shanghai: Local government provides public transit services and the city has an expanding metro system, which has 14 lines and 364 stations (Shanghai Shentong Metro Group Co., Ltd., 2008). The metro system covers downtown area and connects to most neighboring districts. Shanghai Metro is the trunk system in the case study and the system parameters are based on observations from satellite images from Google Earth (Google, n.d.) and the Shanghai Metro system map.

Table 6 Study cities and estimated parameters

Cities	Income Levels	L [km]	Trip Density [trips/km^2-hr]	s [km]	H [hr]	p	s_f [km]
Seattle	high-income	20	50	0.3	0.14	4	0.56
Los Angeles	high-income	40	50	1.7	0.18	6	0.38
Shanghai	low-income	30	250	1	0.07	1	0.15*

*Shanghai has a hybrid bike sharing system with conventional bike sharing and station-less bike sharing. Assuming the bike sharing system is station-less in this case. The total number of shared bikes in Shanghai is about 280,000 (Shanghai Municipal Government, 2017). The calculation for the s_f assumes virtual bike station that holds 10 bikes but without station cost. The effect of station-less bike sharing systems will be discussed in the following sections. The calculation of agency costs and GHG emissions will be modified. The "stations" in a station-less system only incur bike rack cost. The GHG emissions from a virtual station is 2% of the emissions from a regular station. The emission factor from a virtual station E_S will be 3.4 [CO_2e g/(veh-hr)].

4.2 Transportation Systems and GHG Emissions

Background

According to a report by the United Nations Human Settlements Programme, the world's cities are responsible for up to 70 percent of GHG emissions (UN-HABITAT, 2011). With global trends towards increasing urbanization, especially in developing countries, GHG emissions are likely to increase if no corrective actions are taken. Joan Clos, the executive director of UN-Habitat has stated that "cities are responsible for the majority of our harmful gases. But they are also places where the greatest efficiencies can be made." (United Nations Human Settlements Programme, 2011)

Among all sources of GHG emissions, transportation is responsible for 13 percent of global GHG emissions (UN-HABITAT, 2011). Therefore, urban transportation system is an ideal target for local authorities working to reduce GHG emissions. New transportation technologies such as electrical cars and autonomous vehicles have been helping to reduce GHG emissions. However, innovations in mass transit have thus far not been as progressive. Most city authorities would still turn to conventional public transport technologies when looking to improve the city accessibility.

Public transportation provides many opportunities for reducing GHG emissions. The life cycle GHG emissions of public transportation is significantly lower the emissions from individuals driving (Hodges, 2010). Better designed public transportation systems could attract even more commuters to use public transportation as opposed to driving, helping to reduce overall GHG emissions (Daganzo, 2010). Public transportation also facilitates compact land use, which plays a role in GHG reduction (Hodges, 2010).

The integration of bike sharing systems into public transportation networks could further reduce GHG emissions for the following reasons:

From the numerical experiment, introducing bike sharing systems always lower the user costs. Regarding the elasticity in taking public transportation and driving, the effect of commuters' mode choices could be positive. Demonstrated by another study, bike sharing system appears to be improving urban mobility and lowering dependency on automobile travel (Martin & Shaheen, 2014). The implementation of effective bike sharing systems may help encourage commuters to shift away from driving and toward the use of public transportation systems.

Introducing bike sharing system could also reduce the life cycle GHG emissions of public transportation networks. This reduction could be as high as 80%. The model for life cycle GHG emissions is explicitly explained in the following section.

The implementation of bike sharing systems includes the promotion of general bike facilities and could have a positive effect on land use planning. One classic example of how transportation can affect land use planning is Transit Oriented Development (TOD). TOD is a type of community development that includes mixed use and high density development near transit stations (Cervero, 1998). TOD guidelines always include pedestrian amenities and bicycle facilities to promote alternative travel options (Executive Office of Energy and Environmental Affairs, 2007). Introducing bike sharing systems may have positive effects on increasing density in city centers, which facilitates compact land use and could lead to GHG reductions. Facilities such as bike lanes and racks are integrated into the cost function of the proposed trunk-feeder model.

GHG emissions module

The infrastructure life cycle GHG emissions have been calculated in a simple formula compatible to the proposed trunk-feeder model (Griswold, Sztainer, Lee, Madanat, & Horvath, 2017). The revised edition of this formula is applied in this section to calculate the effect on GHG emissions derived from introducing bike sharing systems in to public transit networks. This formula is,

$$Emission\ (CO_2e\ \ g/h) = E_I \times 2L + E_S \times S + E_V \times V$$

with emission factors for both trunk system and bike sharing system,

Table 7 Trunk lines emission factors (Appendix. G)

	E_I – infrastructure [CO_2e g/(km-hr)]	E_S- station infrastructure [CO_2e g/(station-hr)]	E_V- operating and fleet [CO_2e g/(veh-km)]
Bus	8.1	170	1700
BRT	160	1700	2200
Rail	11000	120000	11000
Bike	2.87	170	47.08

Table 8 Study cities' GHG emissions [tonne/hr] (and percentage change)

Cities	Current System	Trunk Only Optimal Scenario	Mixed System Optimal Scenario
Seattle	186.10	41.43 (-78%)	35.87 (-80%)
Los Angeles	55.29	141.03 (155%)	139.31 (152%)
Shanghai	785.31	144.22 (-82%)	173.07 (-78%)

The results imply that not all cities see a reduction in GHG emissions from the introduction of bike sharing into their public transit systems. Compared with current situation of public transit in those cities, optimizing the transportation system could have positive or negative effect on GHG emissions from public transit. For cities, such as Seattle and Shanghai, optimizing the transit system reduces the GHG emissions by about 80%. This figure does not include the emissions reduction attributed to commuters shifting from driving to public transit. Thus, the actual reduction in GHG emissions could be even more significant. For some cities like Los Angeles, which is big and sparsely populated, optimizing the transportation system increases GHG emissions from public transit. This could be a result of improving service by constructing much more transit facilities. But another study also addressed that bike sharing system could reduce automotive travel, especially for bike sharing households that own cars. Bike sharing appears to have reduced automobile emissions (Shaheen, Zhang, Martin, & Guzman, 2011). The overall effects require further studies.

4.3 City Transportation Development Policy

Transportation infrastructure development is critical to the sustainability of the cities and important for urban economics. However, political support and sufficient funds are always present challenges in the development of complex and expensive transportation infrastructure. Transportation facilities sometimes cost billions of dollars and takes decades to complete. Because of this “sunk” characteristic of transportation facilities, the planning of transportation facilities retains the risk of not properly accounting for future demand. It is difficult to perfectly forecast future transit demand and to leave space for contingencies. In addition, there are opportunity costs incurred by not promoting regional transportation facilities. The ability to plan transit system taking into consideration future development could be helpful in designing current transit facilities.

Bike sharing systems are more flexible in application as compared to other more expensive modes of public transit systems. Station-less bike sharing systems can be more flexible because stations can be replaced by applications on mobile phones. Bike lanes can be shared with other cyclers if not utilized by a bike sharing system. If implementing bike sharing can help promote the improved performance of trunk systems, it is feasible for cities to enact policies and provide grant funds to support bike sharing systems as important elements of transit systems.

Some action is already being taken to enact policies that would support bike sharing systems. The Bikeshare Transit Act was introduced by Representative Earl Blumenauer and Representative Vern Buchanan on 7 Jan. 2016. The purpose of the Bikeshare Act is to allow bike sharing projects to be eligible for funding from the Federal Transportation Authority (FTA) (Mcleod, 2016). The Bikeshare Transit Act defines bike sharing projects to include the development of systems with or without rental stations. The Act also provides eligibility for funding to projects, under the Congestion Mitigation and Air Quality Improvement Program, which reduce demand for roads through bike sharing (Congress, 2016).

The model proposed in this thesis is attempts to prove that bike sharing systems can generate benefit for the public, even before performing a cost-benefit analysis. This benefit will be in time saving for commuters or from direct cost savings for transit agencies. The indirect benefit from this model would be reductions in GHG emissions.

The following section will discuss system configurations and changes in costs after optimizing current transportation systems and implementing bike sharing in the cities studied. The effects of optimization and implementation are distinct in the three cities studied. Therefore, policies regarding the promotion of public transit and bike sharing systems should be different based on the particular characteristics of a given city.

Table 9 System Configuration and Costs of Seattle & Los Angeles

	Seattle			**Los Angeles**		
	Current System	Optimum w/o Bike Sharing	Optimum with Bike Sharing	Current System	Optimum w/o Bike Sharing	Optimum with Bike Sharing
Transit Technology	Rail	Bus	BRT	Rail	BRT	BRT
s [km]	0.30	0.64	1.59	1.70	0.80	1.79
r [km]	1.20	0.64	3.17	10.20	1.61	3.58
H [min]	8.40	6.19	2.91	10.80	3.84	2.74
sf [km]			0.54			0.59
Commercial Speed [km/h]	17.14	18.86	33.06	41.63	28.28	33.72
Bike Station Density [/km^2]			3.41			2.90
User Cost [$]	26.19	22.66	16.05	76.24	32.31	24.47
Agency Cost [$]	65.44	2.55	4.74	3.72	6.16	4.30
Total Cost [$]	91.63	25.21	20.79	79.96	38.47	28.77

In table 9, optimizing the current transportation system has a good effect on reducing total costs and user costs. However, in Los Angeles the agency costs nearly double after optimizing the current system without also implementing bike sharing. This could indicate a lack of public transit facilities in the city. In looking at the implementation of bike sharing systems, both Seattle and Los Angeles have lower generalized costs than optimal without bike sharing systems. This is mainly a result of decreased user costs. Implementing bike sharing did not impact agency costs in a consistent manner. Implementing bike sharing system increased agency costs in Seattle but decreases agency costs in Los Angeles. Implementing a bike sharing system keeps agency costs close to those of the current situation in Los Angeles. In conclusion, implementing bike sharing systems reduces user costs in both cities and reduces agency costs in large, sparsely populated, hi-income cities such as Los Angeles.

Table 10 System Configuration, Costs and GHG emission of Shanghai

	Current System	Optimum w/o Bike Sharing	Optimum with Conventional Bike Sharing	Optimum with Station-less Bike Sharing
Transit Technology	Rail	Bus	BRT	BRT
s [km]	1.00	0.71	1.92	1.92
r [km]	1.00	0.71	1.92	1.92
H [min]	4.20	3.59	2.00	2.00
sf [km]			0.49	0.48
Commercial Speed [km/h]	34.29	19.34	34.08	34.08
Bike Station Density [/km^2]			4.19	4.42
User Cost [$]	3.51	4.36	2.76	2.75
Agency Cost [$]	9.61	0.71	1.53	1.53
Total Cost [$]	13.12	5.07	4.29	4.28
Trunk GHG Emission [CO2 e tonne/hr]	785.31	144.22	171.78	172.99
Bike Sharing GHG Emission [CO2 e tonne/hr]			1.29	0.07
Total GHG Emission [CO2 e tonne/hr]	785.31	144.22	173.07	173.06

The effects of optimizing the current system and implementing a bike sharing system in Shanghai is similar to the effects found in the Seattle case. The difference is that because the value-of-time is lower in Shanghai, agency costs decrease with user costs raising as a tradeoff. This means that commuters in low-income cities can bear longer commuting times and prefer spending less on transportation facilities. The needed funding could be raised by imposing taxes or through other collections by local governments, in order to fund transportation facilities.

Implementing bike sharing systems help to balance out the tradeoff between user cost and agency cost in optimum without a bike sharing system. Both user costs and agency costs decrease from the current situation. In this case, implementing a bike sharing system seems to be a better solution for urban transportation in mid-sized, densely populated, low-income cities like Shanghai.

There was no obvious difference in effects between station-less bike sharing systems in comparison to conventional bike sharing systems. The results of system configurations and costs were almost identical in both cases. There were some differences in GHG emissions. Station-less bike sharing has lower GHG emissions as compared to conventional bike sharing. However, from a system perspective, the reduced GHG emissions in station-less bike sharing will be balanced out by the increased GHG emissions in its trunk system. Considering other problems generated from those station-less bike sharing programs, such as excessive shared bikes occupying pedestrian's right-of-way in some cities (Huang & Horwitz, 2017), whether cities should adopt station-less bike sharing systems remains arguable.

4.4 Summary

Policies such as the Bikeshare Transit Act are beneficial because they promote bike sharing systems which have the ability to reduce generalized costs and agency costs. These policies provide for more flexible channels for funding bike sharing systems. Sufficient funding and political support sometimes determines the sustainability of bike sharing systems. The story of the Seattle Pronto bike sharing system highlights that funding and political support can play important roles in the expansion of these systems and also help prevent the underutilization of these systems (Small, 2017). Even when supported by high level policies, the implementation of bike sharing systems should be case specific. The discussion in this chapter highlights that cities can experience differing results from the implementation of bike sharing systems, especially in regard to agency costs. User costs are decreased in most cases. Agency costs tend to decrease from the current situation, but for cities that lack of public transportation. The additional facilities required for commuters raise the agency costs.

CHAPTER 5

CONCLUSION

This study provides evidence on the benefits and costs of implementing bike sharing into public transit systems. One finding is that the implementation of a bike sharing system does not necessarily decrease generalized costs. The implementation of bike sharing encourages the use of fast, high-volume trunk transportation technology such as rail systems. However, the upgrading of trunk transportation technology always incurs an increase in agency costs. Introducing bike sharing and optimizing current public transportation systems have different effect on the user costs, agency cost and generalized cost. The effects of bike sharing systems vary across different cities.

In most cases, introducing a bike sharing system decreases user costs and brings benefits to commuters. In cases where bike sharing systems incur additional agency costs, funding gaps could be problematic and delayed implementation could be detrimental to bike sharing programs, highlighted through the lesson of Seattle Pronto. In cities where introducing a bike sharing system could decrease generalized costs, policy should be implemented to treat bike sharing systems as part of public transportation networks and provide mechanisms to enable sufficient funding. Part of this study highlights that station-less bike sharing systems have similar effects on costs and GHG emissions. Regulations are required to control the size of the bike sharing fleets and prevent these systems from becoming chaotic in nature.

The implementation of a bike sharing does not always decrease GHG emissions from a system perspective. This study gives some insights on life-cycle GHG emissions reduction by introducing bike sharing systems into public transit networks. However, this estimation is based on components of conventional bike facilities like bike lanes and racks. The effects of new components such as data centers and bike sharing stations were ignored, but these effects may not be negligible. Further study on the bike-sharing industry would be helpful in calibrating the emission factors in this model and generating more accurate results on bike sharing life-cycle GHG emissions.

Having this study as reference, future bike sharing systems should consider the potential for these systems to serve as feeders into public transit systems. Detailed policies on implementing bike sharing systems could be proposed to bridge the funding gap and help public agencies work with private sector partners. Bike sharing systems should be treated as an important part of public transit networks and standing policy frameworks for other transportation facilities should be prepared to adapt for the development of bike sharing systems. This study considers implementing bike sharing systems in urban areas with grid street networks. Further studies on other city morphologies, such as core-periphery cities or cities with hub-and-spoke trunk systems, would be helpful in evaluating the value of bike sharing systems.

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Appendix A. Derivation of cost functions

User costs (derivation)	
$A_f = \frac{s_f}{2v_a}$	access time
$Y_f = H + t_r + 2t_{f-t}$	waiting time
$T_f = \frac{2L}{3v_t} + \frac{2L\tau}{3s} + \frac{(p+1)s}{2v_f}$	riding time
Agency costs (derivation)	
$\pi(I_{fl}) = \pi_{Il}\frac{2L^2}{ps} + \beta_{Il}\frac{2ps^2}{s_f}\frac{l^2}{ps^2} = \pi_{Il}\frac{2L^2}{ps} + \beta_{Il}\frac{2L^2}{s_f}$	infrastructure line cost
$\pi(I_{fs}) = \pi_{Is}\frac{2L^2}{ps^2} + (\beta_{Is} + \beta_{Ir} * 1.75\, b)\left(\frac{ps^2}{s_f^2} + 1\right)\frac{l^2}{ps^2}$ $= \pi_{Is}\frac{2L^2}{ps^2} + (\beta_{Is} + \beta_{Ir} * 1.75\, b)\left(\frac{L^2}{s_f^2} + \frac{L^2}{ps^2}\right)$	infrastructure station cost
$\pi(V) = \pi_V\frac{4L^2}{psH} + \beta_V\frac{(p+1)bs}{2}\left(\frac{ps^2}{s_f^2} + 1\right)\frac{l^2}{ps^2}$ $= \pi_V\frac{4L^2}{psH} + \beta_V\frac{(p+1)bsL^2}{2}\left(\frac{1}{s_f^2} + \frac{1}{ps^2}\right)$	distance dependent operating cost
$\pi(M) = \pi_M\left(\frac{4L^2}{v_t psH} + \frac{4L^2\tau}{ps^2H}\right) + \beta_M b\left(\frac{ps^2}{s_f^2} + 1\right)\frac{l^2}{ps^2}$ $= \pi_M\left(\frac{4L^2}{v_t psH} + \frac{4L^2\tau}{ps^2H}\right) + \beta_M bL^2\left(\frac{1}{s_f^2} + \frac{1}{ps^2}\right)$	time dependent operating cost

Appendix B. Estimation for bike technology parameters

Parameters	Values	Comments
Time per Transfer	20	Estimate, same as transfer time of BRT.
Lost Time per Station	0	Bike does not stop at intermediate stations.
Cruising Speed	12	A travel speed estimate of 12 km/h is broadly consistent with a study on bike share travel velocity (Jensen, Rouquier, Ovtracht, & Robardet, 2010).
Passenger Capacity	1	1 user per bike.
Line Capacity	3800	The bike lane capacity is set to 2500 bicycles/h per meter (Zhou, Xu, Wang, & Sheng, 2015), and bike lane width is 5 feet (Arizona Bike Law, 2010).

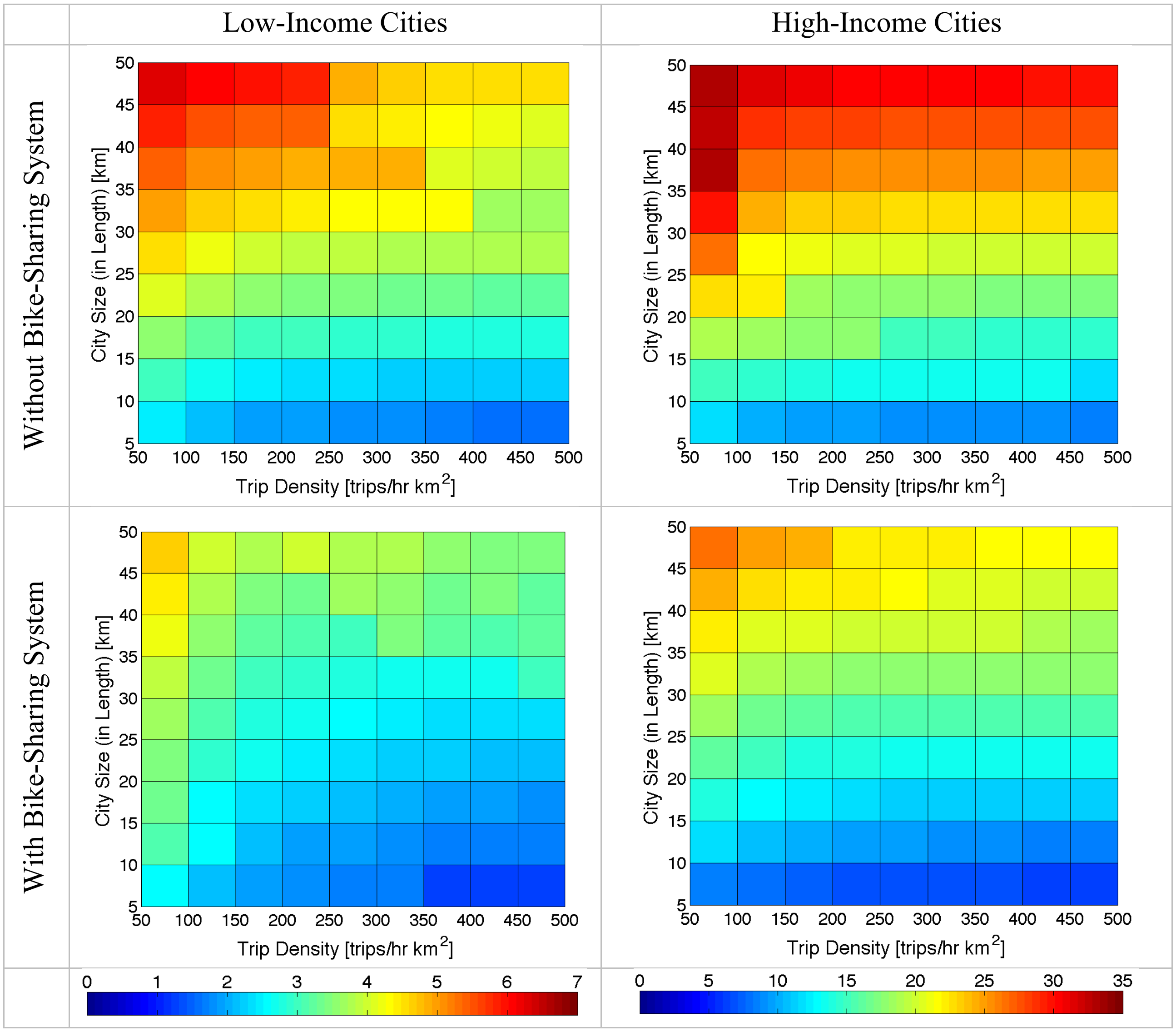
Appendix C. Estimation for coefficients of bike sharing system in low-income cities

	Parameters	Values	Comments
Infrastructure Costs	Lifespan [years]	5	Life span of bike lane pavement (NACTO, n.d.)
	Lifespan [hours]	31,500	
	Infrastructure Line Cost [$/mile]	343,200	$13/ sq ft. (NACTO, n.d.) and 5 ft. width (Arizona Bike Law, 2010)
	Infrastructure Line Cost [$/km]	552,552	
	Amortized Infrastructure Line Cost, C-IL [$/km-hr]	17.541	
	Infrastructure Station Cost [$/station]	26,000	Philadelphia Bike Share Strategic Business Plan (Toole Design Group, LLC and Foursquare ITP, 2013)
	Infrastructure Station Cost [$/station]	27,196	In 2017 dollars
	Amortized Infrastructure Station Cost, C-IS [$/station-hr]	0.432	
	Infrastructure Rack Cost [$/station]	660	(Bushell, Poole, Zegeer, & Rodriguez, 2013)
	Infrastructure Rack Cost [$/station]	690	
	Amortized Infrastructure Rack Cost, C-IR [$/station-hr]	0.011	
Operating Cost			
	Maintenance Cost per Vehicle-Mile [$/veh-mi]	0.1	(Roth, 2011)
	Cost per Veh-Mile, C-V [$/veh-km]	0.1	
Operating Costs (Time)	number of Employees per Vehicle	0.004	16 inspectors per 4000 bikes (Landa, 2014)
	Average Wage [$/hr]	3	(Sivakumaran, Li, Cassidy, & Madanat, 2014)
	Labor Cost per Hour [$/hr]	0.020	
	Purchase Price of Vehicles [$]	1,000	Estimated based on high-income parameters
	Vehicle Lifespan [years]	4	(Tencent Technology News)
	Vehicle Lifespan [hr]	25,200	
	Depreciation per Hour [$/hr]	0.040	
	Maintenance Cost per Vehicle-hour [$/veh-hr]	0.000	$\$5*10^{6}$ /veh-hr (Zhang, Zhang, Duan, & Bryded, 2015)
	Cost per veh-hr, C-M [$/veh-hr]	0.060	

Appendix D. Estimate for coefficients of bike sharing system in high-income cities

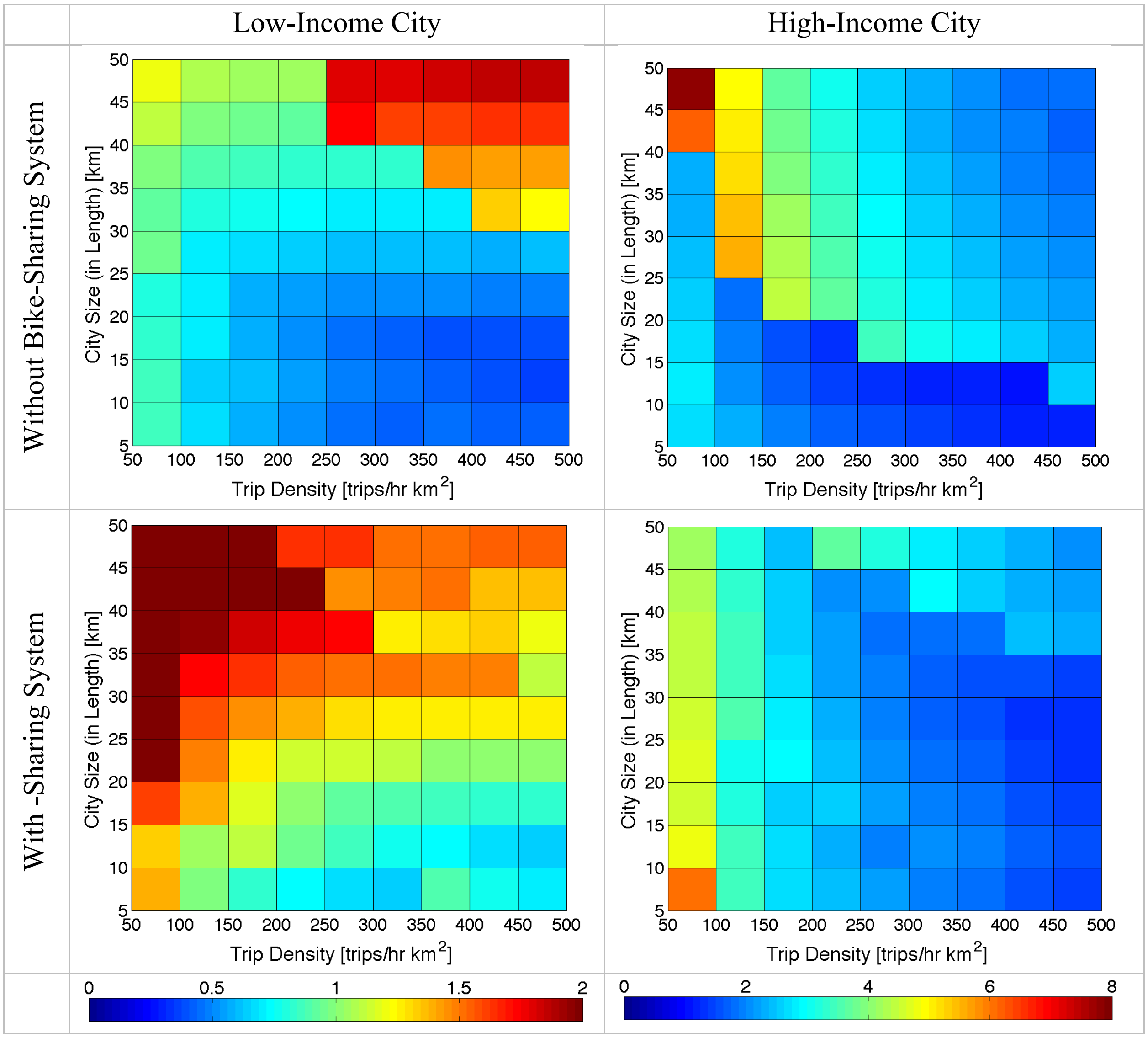
	Parameters	Values	Comments
Infrastructure Costs	Lifespan [years]	5	Life span of bike lane pavement (NACTO, n.d.)
	Lifespan [hours]	31,500	
	Infrastructure Line Cost [$/mile]	435,600	$16.5/ sq ft. (NACTO, n.d.) and 5 ft. width (Arizona Bike Law, 2010)
	Infrastructure Line Cost [$/km]	701,316	
	Amortized Infrastructure Line Cost, C-IL [$/km-hr]	22.264	
	Infrastructure Station Cost [$/station]	50,000	(Kurtzleben, 2012)
	Infrastructure Station Cost [$/station]	53,050	In 2017 dollars
	Amortized Infrastructure Station Cost, C-IS [$/station-hr]	0.84	
	Infrastructure Rack Cost [$/station]	660.00	(Bushell, Poole, Zegeer, & Rodriguez, 2013)
	Infrastructure Rack Cost [$/station]	690.36	In 2017 dollars
	Amortized Infrastructure Rack Cost, C-IR [$/station-hr]	0.011	
Operating Cost			
	Maintenance Cost per Vehicle-Mile [$/veh-mi]	0.1	(Roth, 2011)
	Cost per Veh-Mile, C-V [$/veh-km]	0.1	
Operating Costs (Time)	number of Employees per Vehicle	0.0040	16 inspectors per 4000 bikes (Landa, 2014)
	Average Wage [$/hr]	20	(Sivakumaran, Li, Cassidy, & Madanat, 2014)
	Labor Cost per Hour [$/hr]	0.08	
	Purchase Price of Vehicles [$]	2,200	Philadelphia Bike Share Strategic Business Plan (Toole Design Group, LLC and Foursquare ITP, 2013)
	Vehicle Lifespan [years]	5	
	Vehicle Lifespan [hr]	31,500	
	Depreciation per Hour [$/hr]	0.070	
	Maintenance Cost per Vehicle-hour [$/veh-hr]	0.01528	(Bushell, Poole, Zegeer, & Rodriguez, 2013)
	Cost per veh-hr, C-M [$/veh-hr]	0.165	

Appendix E. User cost of transportation systems



The trends in user costs are similar for both low-income and high-income cities. High-income cities have higher user costs in general because of the higher value-of-time for individuals in these cities. For large cities, bike sharing has more benefits for low and medium density low-income cities and high density high-income cities. These savings may be derived from the tradeoff between user costs and more expenditure on infrastructure. These effects were discussed in the comparison section of Chapter 3.

Appendix F. Agency cost of transportation systems



For large, low density cities, introducing bike sharing systems has distinct effects for low-income cities and high-income cities. For low-income cities, introducing a bike sharing system significantly increases transportation agency costs. However, for high-income cities, introducing a bike sharing system decreases transportation agency costs. This could result from the changing in optimal transit technology.

Appendix G. Bike sharing emission factors (calculation)

	Parameter	Value	Comments
Bus	E_I - infrastructure [CO_2e g/(km-h)]	8.1	(Griswold, Madanat, & Horvath, 2013)
	E_S- station infrastructure [CO_2e g/(station-hr)]	170	
	E_V- operating and fleet [CO_2e g/(veh-km)]	1700	
BRT	E_I – infrastructure [CO_2e g/(km-h)]	160	
	E_S- station infrastructure [CO_2e g/(station-hr)]	1700	
	E_V- operating and fleet [CO_2e g/(veh-km)]	2200	
Rail	E_I - infrastructure [CO_2e g/(km-h)]	11000	
	E_S- station infrastructure [CO_2e g/(station-hr)]	120000	
	E_V- operating and fleet [CO_2e g/(veh-km)]	11000	
Bike	E_I - infrastructure [CO_2e g/(km-h)]	2.87	271.1 kg /350/18/15 (Matute, 2016)
	E_S- station infrastructure [CO_2e g/(station-hr)]	170	Same as bus
	E_V- operating and fleet [CO_2e g/(veh-km)]	47.08	42.6+4.48 (Matute, 2016)

Appendix H. Study cities and estimated parameters

Cities	Income Levels	s	H	p	sf
Seattle	high-income	0.3 (Sound Transit, n.d.)	0.14 (Sound Transit, 2017)	4	0.56 (City of Seattle, 2014)
Shanghai	low-income	1 (Google, n.d.)	0.07 Wikipedia: Line 1, Shanghai Metro (Wikipedia, 2017)	1	0.15*
Los Angeles	high-income	1.7 (Los Angeles County MTA, n.d.)	0.18 Wikipedia: Los Angeles Metro Rail (Wikipedia, n.d.)	6	0.38 (Metro Bike Share, 2016)

* The average distance between virtual bike stations for station-less bike sharing system.