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16. ABSTRACT

Public transit systems with efficient designs and operating plans can reduce greenhouse gas (GHG) emissions relative to low-occupancy transportation modes, but many current transit systems have not been designed to reduce environmental impacts. This motivates the study of the benefits of design and operational approaches for reducing the environmental impacts of transit systems. For example, transit agencies may replace level-of-service (LOS) by vehicle miles traveled (VMT) as a criterion in evaluating design and operational changes. Previous studies have demonstrated in an idealized single-technology transit system the potential of reducing GHG emissions by lowering the transit level-of-service (LOS) provided to the users.

In this research, we extend the analysis to account for a more realistic case: a transit system with a hierarchical structure (trunk and feeder lines) providing service to a city where demand is elastic. By considering the interactions between the trunk and the feeder systems, the study provides a quantitative basis for designing and operating integrated urban transit systems that can reduce GHG emissions and costs to both transit users and agencies. The study shows that highly elastic transit demand may cancel emission reduction potentials resulting from lowering LOS, due to demand shifts to lower occupancy vehi cles, causing unintended consequences. However, for mass transit modes, these potentials are still significant. Transit networks with buses, bus rapid transit or light rail as trunk modes should be designed and operated near the cost-optimal point when the demand is highly elastic, while this is not required for metro. We also find that the potential for unintended consequences increases with the size of the city. The results are robust to uncertainties in the costs and emissions parameters.

The study also includes a discussion of a current transit system. Since many current transit systems have not yet been optimally designed, it should be possible to reduce their GHG emissions without sacrificing the LOS. A case study of the MUNI bus system in San Francisco is used to validate this conjecture. The analysis shows that reductions in GHG emissions can be achieved when societal costs are reduced simultaneously. The cost-optimal MUNI bus system has a societal cost of 0.15 billion $/year and emits 1680 metric tons of greenhouse gases. These figures only amount to about half of the cost and a third of the emissions in the current MUNI bus system. The optimal system has a lower spatial availability but a higher temporal availability of bus service than the current system, which highlights the potential benefits of providing more frequent express bus services .

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Potential Greenhouse Gas Emission Reductions from Optimizing Urban Transit Networks

Final Report

CALIFORNIA DEPARTMENT OF TRANSPORTATION

Potential Greenhouse Gas Emission Reductions from Optimizing Urban Transit Networks

May 2016

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Chapter 1 Introduction

1.1 Background

In recent years, public transportation's role in reducing greenhouse gas (GHG) emissions has started to receive increased attention. Compared to private automobiles, studies suggest that public transit systems with high occupancy rates and efficient designs can reduce GHG emissions significantly (Hodges 2009). However, many current transit systems are not designed to reduce environmental impacts. For example, in the United States, the average energy intensity of transit buses is even higher than passenger cars due to the current low ridership rate of urban buses (Davis et al. 2009, Chester and Horvath 2009). There have been many efforts in the transit sector to reducing transit GHG emissions. However, many of them have focused on vehicles and fuel technologies, such as employing efficient replacement vehicles and changing to alternative fuels.

Another potential approach to reducing transit GHG emissions is through lowering the operational frequency and spatial coverage, i.e., the level of service (LOS). Though unconventional and undesirable to captive transit users, it would not be the first time this idea has been explored: the literature contains at least two examples where cities have explored increases in stop spacings to reduce GHG emissions (Shrestha and Zolnik 2013, Saka 2003). Furthermore, intentionally lowering LOS is a possible course of action for cities that are not using LOS requirements for their transportation projects. Policy may also support this, such as the recent example of Californian legislation, Senate Bill 743 (California SB 743 2013), which authorizes cities to opt out of LOS requirements and use other criteria for evaluating impacts of transportation projects. In developing new criteria, SB 743 recommends adopting metrics such as vehicle miles traveled (VMT), which have the potential to reduce GHG emissions.

This line of action has been partially verified by the study for a trunk transit system designed to minimize societal costs while serving a fixed demand density: the reductions in GHG emissions can be achieved by reducing the LOS of the trunk transit system provided to the users (Griswold et al. 2013). However, this might not hold for the more realistic case where transit demand is elastic. With elastic demand, the reductions in the transit LOS, aimed at reducing the transit GHG emissions, may lead to a city-wide increase in the GHG emissions as some transit users may not tolerate the reduction in service and will switch to faster but more polluting modes, such as private automobiles. This would be a problem for cities that plan to take advantage of the flexible metrics allowed by SB 743. Therefore, it is necessary to consider transit demand elasticity before following such a potential action.

Urban transit networks in reality are usually hierarchical, consisting of not only the trunk transit service but also the feeder transit service that serves local demand and trunk access demand. Instead of walking, transit passengers may use feeder modes to access trunk transit. Both SB 743 and California Assembly Bill 1358 (AB 1358) have addressed the need for promoting the development of a balanced multimodal transportation system to meet the travel needs of all users with different O-D pairs. In order to achieve significant improvement in environmental conditions of a multimodal transportation system, studies suggest that all modes should be considered as parts of an integrated system, and that modifications to one component should consider their effect on the whole system (Rondinelli and Berry, 2000). Sivakumaran et al. (2014) find that capital-intensive and large-capacity transit technologies, such as metro, are economically feasible only when combined with other transit technologies that act as feeders. As a result, it is necessary to integrally study transit systems instead of concentrating on each element separately.

The objective of this research is to examine the potential extent to which an optimally designed urban transit system reduces GHG emissions while considering transit demand elasticity and integrated transit hierarchy. A transit system is optimally designed if it minimizes total societal costs, i.e., the sum of user and agency costs. A transit network is hierarchical when it consists of feeder and trunk modes. Transit users may choose a single or any sequence of different modes to complete their travels based on the locations of their origins and destinations. In this study, a simplified hierarchical grid transit network with uniformly distributed elastic demand is adopted as a theoretical case for testing the model. The hierarchical grid transit network consists of lines for the trunk transit mode and lines for the feeder transit mode. By quantifying the LOS-emissions relationship for an idealized hierarchical transit system, the research will inform policies for cities that plan to take advantage of the flexible metrics allowed by SB 743. Particularly, reductions in GHG emissions at the expense ofreducing transit LOS are quantified, highlighting the advantages and potential pitfalls associated with shifting from an LOS-based standard to a VMT criterion in evaluating transit projects or operational changes.

It should also be noted that it is possible for many transit systems to reduce VMT and GHG emissions without reducing transit LOS, because many of them have not been optimally designed to achieve minimum costs. As a result, in the latter part of the research, we extend the work to analyze such a transit system, the MUNI bus network for the city of San Francisco. We build a mathematical model of the MUNI bus network to obtain a relatively accurate representation of the current network. The societal costs and emissions of the current MUNI system are quantified. The potentials for emissions reductions and the changes in LOS are then discussed for the MUNI system.

1.2 Summary of Findings

The main findings of this research are:

(i) In large cities, hierarchical transit systems with mass transit modes (metro, for example) tend to be more cost- and emission-efficient. However, in small cities, trunk-only bus systems may be more favorable with regards to both costs and em1ss1ons savmgs.

(ii) Transit demand elasticity offsets transit emissions reduction efforts by causing additional automobile emissions due to demand shifting away from transit. Transit agencies should evaluate the demand elasticity in areas of interest before trying to reduce emissions through lowering transit LOS.

(iii) The process of transit cost minimization may also reduce GHG emissions.

Chapter 2 Literature Review

This literature review consists of three parts. The first part discusses the GHG emissions inventories from public transportation. The second part discusses current approaches to reducing public transit emissions. The third part describes different methodologies for solving transit network design problems.

2.1 Emissions from public transportation

With all the combustion of petroleum-based products, GHG emissions from transportation have accounted for about 28% of total GHG emissions in the United States, making it the second largest contributor after the electricity sector (EPA 2014). This highlights the need to better understand the GHG emissions in transportation. Among all the potential ways to reduce emissions, shifting automobile trips to public transit systems is a common option. However, the GHG emissions from public transit itself are not negligible.

Many studies have attempted to measure the amount of GHG emissions of public transit. Yet most of them have focused on measuring the tailpipe emissions that occur during the vehicle operations phase and are largely dependent on the vehicle-miles-traveled (Small 1988, Faiz 1996, Prucz et al. 2001, Turrio-Baldassarri et al. 2003, Nylund et al. 2004, Wayne et al. 2004 and 2008, Shorter et al. 2005, Vincent et al. 2006, Zhai et al. 2008, Hesterberg et al. 2008, Tong et al. 2011, Lau et al. 2011, Li et al. 2012). Davis and Hale (2007) analyze the GHG emissions inventory of public transit based on the estimations of total passenger-miles-traveled, mode splits of bus and rail, and the carbon-dioxide tailpipe emissions factors of transit vehicles. They find that in 2005, the U.S. public transportation sector emits approximately 13 million metric tons of CO2. Weigel et al. (2009) present a calculation tool for estimating the emissions for a complete vehicle operations phase, considering tailpipe exhaust emissions along with other affiliated sources such as fugitive refrigerant emissions.

In a wider scope, transit emissions do not only occur during the vehicle operations phase. Some studies assess the transit emissions over the life cycle of fuel consumption (Sheehan 1998, Beer et al. 2002 and 2004, Brinkman et al. 2005, Puchalsky 2005, Karman 2006, Clark et al. 2007), which may include fuel production, transportation, storage, distribution, and finally combustion. The emissions from these sources are also called wells-to-wheels emissions. Puchalsky (2005) compares the partial fuel-cycle emissions of Light Rail Transit (LRT) and Bus Rapid Transit (BRT), considering both fuel delivery and fuel combustion. Karman (2006) presents a case study of Beijing, measuring the GHG emissions of compressed natural gas (CNG) buses and conventional diesel buses. The analysis defines factors of fuel-based life-cycle emissions that account for both tailpipe emissions and the emissions from all the upstream stages of fuel consumption.

Furthermore, when evaluating a transit system as a whole, the process of manufacturing and repairing transit vehicles, constructing and maintaining the transit infrastructure creates GHG emissions as well. Life-cycle emissions from entire transit systems have not been commonly addressed in the literature. What is available includes: Ally and Pryor (2007) analyze the GHG emissions of diesel, natural gas and hydrogen fuel cell bus systems, introducing both the fuel-cycle emissions and the emissions from bus manufacturing. Cui et al. (2010) present a case study of the BRT system in Xiamen, China. They assess the carbon footprint of Xiamen BRT system on a wider scope that includes vehicle and infrastructure production, maintenance, recycling. Chester and Horvath (2009) and Chester (2008) employ a hybrid life-cycle-assessment model to provide a generalized analysis on the emissions inventory of various transit technologies by considering four emissions sources: fuel production, infrastructure, vehicle operation and vehicle non-operation. The emissions estimation results from Chester and Horvath (2009) and Chester (2008) will be used in this work.

2.2 Approaches to reducing public transit emissions

Environmental Protection Agency (EPA) has suggested using alternative fuels that are less carbon-intensive, improving fuel-efficiency of vehicles, and more compact land-use patterns to reduce passenger-miles-traveled as efforts to mitigate GHG emissions (EPA 2014). There have been many real-world examples corresponding to these categories; mainly as use of alternative fuels such as biodiesel, CNG, LPG and hybrid; retrofitting existing engines or purchasing more fuel-efficient engines; cities that employ transit-oriented development.

Most investments in the transit sector to address GHG emissions have focused on purchasing efficient replacement vehicles and encouraging mode shifts from private automobile by increasing transit LOS (Gallivan and Grant 2010). Those approaches can be expensive. Meanwhile, simply increasing the transit service level, aimed at attracting drivers to the transit systems, can sometimes backfire, causing a net increase in GHG emissions (Griswold et al., 2014). Public transit systems that operate with low ridership rates have been shown to have higher per-passenger-kilometer emissions than the automobile (Davis et al. 2009, Chester and Horvath 2009, Taptich and Horvath 2014). Evaluating the effect of transit system design and operational modifications on GHG emissions is essential.

There have been important studies done in this area, but some questions still remain. Saka (2003) concludes that bus stops impede the flow of traffic, which depending on the traffic intensity can result in congestion and excessive emissions on the bus route. Shrestha and Zolnik (2013) provide a case study of the bus service for the city of Fairfax, Virginia, and find that eliminating some bus stops could improve travel time and reduce operating costs. Bus-related emissions could also be substantially lower after the elimination of the bus stops. Alam and Hatzopoulou (2014) present possible approaches to reducing transit bus emissions on a busy corridor: using alternative fuels or improving traffic operations. They find that improving traffic operations alone, such as applying transit signal priority (TSP) and relocation of bus stops, could significantly reduce GHG emissions.

Beside the redistribution of transit stations, there are other network design and operational modifications that have not been commonly considered, such as improving schedule, changing route spacing, and choosing the best transit technology for the city characteristics. Griswold et al. (2013) provide a thorough investigation of the relation between costs and GHG emissions in transit systems while considering a broad range of potential transit system design and operational modifications. They demonstrate that, for a trunk-only, grid-network transit system designed to minimize societal costs while serving a fixed demand elasticity, a city can achieve reductions in GHG emissions by reducing the transit LOS provided to the users. However, this result might not hold for the more realistic case where transit demand is elastic. The reductions in the transit LOS, aimed at reducing the transit GHG emissions, may lead to a city-wide increase in the emissions as users shift to more polluting modes such as private automobiles. Moreover, Griswold et al. (2013) used a simple trunk system without network hierarchy in their model, which limits the realism of their results. Sivakumaran et al. (2014) suggest that capital-intensive and large-capacity transit technologies, such as metro, are economically feasible only when combined with other transit technologies that act as feeders. A metro system is usually designed with large stop and route spacings. With walking assumed to be the only access mode to the transit system, the trunk-only model utilized in Griswold et al. (2013) may unfairly place metro at a comparative disadvantage. In order to make mode comparisons realistic, it is necessary to incorporate feeder transit modes and to investigate how it affects the comparisons between different trunk transit modes.

2.3 Methods for solving transit network design problems

There have been several studies on optimizing transit system design with respect to minimizing agency and user costs, yet the environmental impacts are rarely addressed (Dessouky et al. 2003; Saka 2003; Diana et al. 2007; Griswold et al. 2013 and 2014). Continuum approximation (CA) methods are widely employed to optimize network attributes such as stop spacing (Kuah and Perl 1988; Parajuli and Wirasinghe 2001) and headway (Chien et al. 2010). Some other studies analyze the structure of transit networks using CA methods, such as grids, radial networks (Byrne 1975; Tirachini et al. 2010), and hub-and-spoke networks (Newell 1979). Based on a grid network, Sivakumaran et al. (2014) use CA methods to quantify the cost-effectiveness of providing bus access to different trunk technologies. While CA methods use stylized transit network types and simplifying approximations, they are able to provide closed-form solutions and allow the identification of cause-and-effect relationship between inputs and design outputs (Daganzo 2010). Furthermore, the results can be implemented by adjusting the optimal design values to existing street networks with minor loss in optimality, as the recent design of the Barcelona high performance bus system has shown (Estrada et al. 2011).

Some studies use heuristic methods instead to solve transit network design problems. Most of them address the complex, non-stylized networks of real cities where it is usually impractical to obtain analytical optimal solutions. With increasing computational capacity of computers in recent decades, meta-heuristic methods such as Genetic Algorithm and Tabu Search and Simulated Annealing are used to find efficient transit routes on existing street networks and efficient timetables for operating transit vehicles (Pattnaik et al. 1998; Yang et al. 1999;

Chakroborty 2003; Fan et al. 2009 and 2010). However, these methods can still be computationally expensive while providing few general insights into the cause-and-effect relationship between inputs and design outputs.

This research will employ CA methods to optimize a hierarchical grid transit network for two objectives: societal costs (the sum of agency and user costs) and GHG emissions.

Chapter 3 Hierarchical Transit System Design

3.1 Network Design

We consider a simplified hierarchical grid transit network. Transit users may choose to use a single or any sequence of transit modes to complete their travels based on the locations of their origins and destinations. The hierarchical grid transit network design is based on the work of Sivakumaran et al. (2014) with the following features:

(1) The hierarchy consists of two levels: the trunk grid framework that outlines the macroscopic shape of the network, and the branch system (also called the feeder system) located within the blocks that are defined by the trunk grid.

(2) Each level of hierarchy has one transit mode. The mode for the trunk system has large capacity, high cruising speed, intensive capital investment, and is designed for long-distance service. The mode for the branch system is slower, cheaper, and mainly for local service and meeting demand to and from the nearest trunk transit stop.

(3) The stops for the trunk network are evenly distributed along the trunk lines, and the route spacing is a multiple of the stop spacing so that we are able to locate a transit stop at each intersection of the trunk lines. Similarly, the stops for the branch network are also evenly distributed along the branch lines. However, the branch network is assumed to be comprised of parallel routes rather than grids so that there are no intersections within each branch system. It is also assumed that all the trunk stops experience the same headway of the trunk transit (H), while all the feeder stops experience the same headway of the feeder transit *(h)*.

(4) The feeder system provides feeder service to the nearest trunk transit stop. Therefore, we can generalize the branch system by picking out a rectangular zone where all branch lines are located in the same trunk grid block and direct to the same trunk stop. The zone is called "sub-block" so as to distinguish this from the trunk grid block.

(5) The demand for transit service is evenly distributed in the entire rectangular area. Every hour in each unit of area there is a certain amount of transit demand generated, defined as transit demand density *(p)*. For each transit user, feeder transit and/or trunk transit may be used based on the locations of the user's origin and destination.

The simplified hierarchical grid transit network is shown in Figure 3.1.

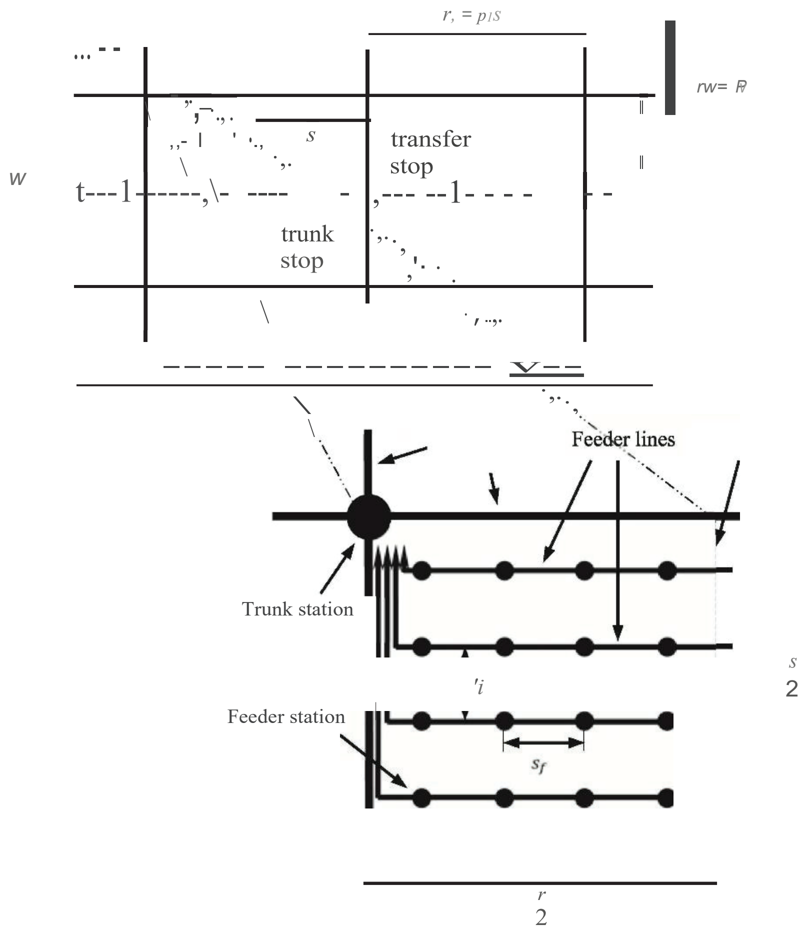


Figure 3.1 Hierarchical transit network for this study

Where:

W, L - Width and length of the transit network.

rw, r_1 - Route spacing for trunk lines.

s - Stop spacing for trunk transit stops.

rt - Route spacing for feeder lines.

St - Stop spacing for feeder transit stops.

The Continuum Approximation (CA) methods are employed to optimize the described hierarchical transit network for two objectives: GHG emissions and societal costs. Demand elasticities are used to predict the impacts of transit service changes. Different trunk line technologies are considered, including heavy rail (metro), light rail transit (LRT), bus rapid transit (BRT), and bus. The feeder systems are operated using the feeder buses and assumed to be accessed by walking.

On average, users in the hierarchical transit system will complete their travels by following the principles below:

(1) If the distance between the origin and the destination is short (lower than a criteria defined as the walk-able distance), the user will complete the travel solely by walking. This is called the "walk" travel.

(2) If the distance between the origin and the destination is larger than the walk-able distance, yet the origin and the destination are still located within the same sub-block, the user will walk to the nearest branch transit stop, take the branch transit within the sub-block, get off at the stop nearest to the destination, and then walk to the destination. This is called the "walk - branch - walk" travel.

(3) If the distance is even longer such that the origin and the destination are located in two different sub-blocks, the user will walk to the nearest branch transit stop and take the branch transit to access the trunk transit, then take the trunk transit to access the branch transit of the sub-block the destination locates in, and finally access the destination by taking that branch transit and walking. This is called the "walk - branch - trunk - branch - walk" travel.

There are some cases where the above principles may appear redundant. For example, when the origin and the destination are located in two adjacent sub-blocks, the user might be better off skipping the trunk transit and completing the travel simply by taking two adjacent branch transit combined with necessary walking access. However, involving these details may significantly increase the complexity of the model without getting much better insights (Sivakumaran et al. 2014). Hence we assume that all the users follow the principles described above.

It should also be noted that the hierarchical network may not be ideal for slow, low-capacity trunk transit technologies, such as buses. A bus system is usually designed with small stop and route spacings. For cities with small geometric sizes, the average travel distances are short. Incorporating a feeder system may cause unnecessary intra-modal transfer times and feeder emissions, and thus a bus system without feeder access might be a better option. However, for large cities, adopting trunk-only bus systems may not be feasible due to limited bus capacity. To verify these conjectures, we also consider trunk-only bus systems for comparison with the hierarchical systems described above.

3.2 General Formulation

The formulation of the problem builds on the work of Sivakumaran et al. (2014) and Griswold et al. (2013). The mathematical formulation consists of optimizing the transit system design to achieve the lowest total costs and transit emissions possible. The problem can be formulated as a constrained optimization (3.1). The objective is to solve for the values of the decision variables that minimize the societal costs subject to a transit emissions constraint. Another constraint comes from the capacity of the transit mode. Decision variables include headways, stop spacings, and route spacings for the trunk and feeder systems: H, h, s, st, rw, rL, rt. The cost and emission terms in (3.1) are functions of these decision variables.

$$\min \; C_{total} = C_{user} + C_{agency}$$

$$s.t.\quad E_{emissions,T} \quad E \tag{3.1}$$

$$Load \quad Kap$$

Where:

C_{total} - Total societal cost.

C_{user} - Cost to the transit users.

C_{agency} - Cost to the transit agencies.

$E_{emissions,T}$ - GHG emissions oftransit system

E - Budget of greenhouse gas emissions

$Load, Kap$ -Transit load and capacity

Solving the constrained optimization problem in (3.1) provides a set of optimal system attributes $(H, h, s, s_1, r_W, r_L, r_1)$ for given emissions goals. By varying the emissions constraint E, we are able to display the set of optimal solutions by drawing a Pareto frontier of E and C_{total}.

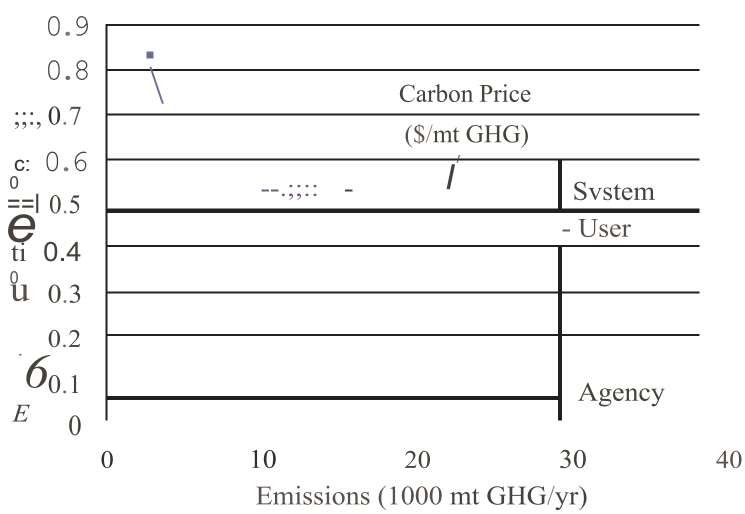


Figure 3.2 Total (system), user, and agency costs for a bus system by GHG emissions level (Griswold et al. 2013)

The Pareto optimality indicates the state where it is impossible to make the costs better off without making the emissions worse off, or vice versa (Griswold et al. 2013). For example, Figure 3.2 shows the optimal societal cost curve for a trunk-only bus system as the GHG emissions constraint varies. The vertical bar at the right of the curve marks the system cost-optimal point, beyond which relaxing E would not produce lower C_{total}. The other end of the curve would be the emission-optimal point, which means if the constraint E is reinforced further, there would be no feasible solutions for the model.

The Pareto frontiers of E and C_{total} can be used to inform transit system design. We are able to quantify, for an efficiently designed transit system, the potential increase in total cost as a consequence of saving transit emissions. Furthermore, the slope of a tangent on the Pareto curve is the shadow price of the emissions constraint, i.e., the marginal societal cost ofreducing emissions by an additional unit. If the carbon price in the market is known, the corresponding point on the Pareto curve can be found where the shadow price is equal to the carbon price. This point may refer to the ideal state that the transit agency wants to achieve because operating the transit system at this point would maximize social surplus, according to economic theory.

The other two curves in Figure 3.2 are obtained by calculating the corresponding user cost C_{user} and agency cost C_{agency} for each optimal C_{total}. The agency costs C_{agency} decrease when emissions are constrained because emissions reductions are caused by reductions in transit LOS, including reduction in bus frequency; as a result, transit VMT is reduced. The user costs C_{user} increase when emissions are constrained because the reductions in the transit LOS, aimed at reducing the transit emissions, increase the average transit travel time.

Since the transit demand is elastic, one would also expect that the reductions in the transit LOS have the potential of causing additional emissions of other modes due to the transit demand shifts, leading to unintended emissions consequences. We will examine how the city-wide GHG emissions are affected by the changes in demand due to the reductions in the transit LOS. By incorporating travel time elasticities into the model formulation, one can estimate the fraction of users who will switch to a faster mode, typically the automobile. The specific descriptions can be found in Section 3.3.

3.2.1 Cost to transit users

The cost to transit users is measured by monetized average travel time. We first analyze the components of the average travel time for a transit user by employing CA methods, and then obtain the total travel time for all the transit users per time unit by multiplying the transit demand. The average travel time for a transit user is:

$$T_{average} = \frac{r_r}{v_a} + h_t + (0.5r_L + 0.5r_W + s)\frac{1}{2v_t} + (0.5r_L + 0.5r_W)\frac{1}{2s_t} + H + T + 2T_{intra} + (L + W)\left(\frac{}{3v_t} + \frac{..}{3s}\right) \quad (3.2)$$

Where:

r_t - Route spacing for feeder lines (km)

r_W, r_L - Route spacing for trunk lines (km)

W, L - Width and length of the transit network (km)

s - Stop spacing for trunk transit stops (km)

s_t - Stop spacing for feeder transit stops (km)

v_a - Speed of walking (km/h)

V_t - Cruising speed of feeder transit (km/h)

V_t - Cruising speed of trunk transit (km/h)

h_f - Headway of feeder transit (min)

H - Headway of trunk transit (s)

T - Average transfer time within trunk transit (s)

T_{intra} - Average transfer time between trunk transit and feeder transit (s)

τ_f - Average dwelling time at each feeder transit stop (s)

τ - Average dwelling time at each trunk transit stop (s)

The terms are explained as below:

$r\frac{1}{V_a} + h_f$ - Time spent for walking to and waiting for the feeder transit

$(0.5rL + 0.5rw + s)\frac{2}{2V_f}$ - Feeder transit cruising time

$(0.5rL + 0.5rw)\frac{\tau_f}{2r_f}$ - Feeder transit dwelling time

$H + T + 2T_{intra}$ -Average waiting and transfer time

$(L+W)\left(\frac{2}{3V_t} + \frac{\tau}{3s}\right)$ - Trunk transit cruising and dwelling time

The cost to all the transit users is obtained by multiplying $T_{average}$ with the transit demand and the value of time as below:

$$C_{user} = T_{average}\,\mu pLW \tag{3.3}$$

μ - Value of time to transit users **($/h)**

p - Transit demand density (pax/km^2-h)

3.2.2 Cost to transit agencies

The cost to transit agencies results from construction and maintenance of transit infrastructure, vehicle purchase and maintenance, fuel purchase and labor employment. Griswold et al. (2013) employed cost factors that averaged these cost terms with appropriate units. For example, the cost of vehicle purchase and maintenance, and fuel purchase are grouped together and averaged for each vehicle kilometer traveled, forming a cost factor C_V ($/veh-km). The labor cost is averaged on a time basis, forming a cost factor C_M ($/veh-km), because it relates closely to how long employees work. In this study, we adopt the same methodology to obtain cost factors for both the trunk transit and the feeder transit.

We quantify the cost to transit agencies by analyzing the trunk transit and the feeder transit individually, and then summing them together as in (3.4):

$$C_{agency} = C_{agency,Trunk} + C_{agency,Feeder} \tag{3.4}$$

The cost of the trunk transit is obtained from Griswold et al. (2013) as below:

$$C_{agency,\ Trunk} = \frac{LW}{s}\left(\frac{2}{p_W}+\frac{2}{p_L}\right)C_I + \frac{2LW}{sH}\left(\frac{2}{p_W}+\frac{2}{p_L}\right)C_V + \frac{2LW}{sH}\left(\frac{2}{p_W}+\frac{2}{p_L}\right)\left(\frac{}{v}+\frac{}{s}\right)C_M + \frac{LW}{s^2}\left(\frac{2}{p_W}+\frac{2}{p_L}\right)C_S \tag{3.5}$$

C_I - ROW infrastructure cost ($/km-h)

C_V - Vehicle purchase, fuel & maintenance cost ($/veh-km)

C_M - Labor cost ($/veh-h)

C_S - Station construction cost ($/st-h)

The cost of the feeder transit is defined as below:

$$C_{agency,Feeder} = \frac{2LW}{r_f^2}C_{S,f} + \frac{LW}{r_f h_f}\left(4+\frac{1}{p_W}+\frac{1}{p_L}\right)C_{V,f} + \frac{LW}{v_f r_f h_f}\left(4+\frac{1}{p_W}+\frac{1}{p_L}\right)C_{M,f} + \frac{4LW\tau_f}{h_f r_f^2}C_{M,f} \tag{3.6}$$

$C_{I,t}$ - ROW infrastructure cost for feeder ($/km-h)

$C_{V,t}$ - Feeder purchase, fuel & maintenance cost ($/veh-km)

$C_{M,t}$ - Feeder labor cost ($/veh-h)

$C_{S,t}$ - Feeder station construction cost ($/st-h)

3.2.3 Transit and auto emissions

Transit life cycle emissions result from construction and maintenance of transit infrastructure, vehicle manufacture, operation and maintenance. Similarly to the transit agency costs, these emissions terms are also averaged with appropriate units.

We model the emissions of the trunk transit and the feeder transit individually, and then sum them together to formulate the total emissions of the transit system as in (3.7):

$$E_{emissions,T} = E_{emissions,Trunk} + E_{emissions,Feeder} \tag{3.7}$$

The emissions of the trunk transit are obtained from Griswold et al. (2013) as below:

$$E_{emissions,Trunk} = \frac{LW}{s}\left(\frac{2}{p_W}+\frac{2}{p_L}\right)E_I + \frac{2LW}{sH}\left(\frac{2}{p_W}+\frac{2}{p_L}\right)E_V + \frac{LW}{s^2}\left(\frac{2}{p_W}+\frac{2}{p_L}\right)E_S \tag{3.8}$$

E_I - ROW infrastructure emissions (g/km-h)

E_V - Vehicle fleet manufacturing, operation & maintenance emissions (g/veh-km)

E_S - Station construction emissions (g/st-h)

The emissions of the feeder transit are defined as below:

$$E_{emissions,feeder} = \frac{2LW}{r_f^2}E_{S,f} + \frac{LW}{r_f h_f}\left(4+\frac{2}{p_W}+\frac{2}{p_L}\right)E_{V,f} \tag{3.9}$$

$E_{l,t}$ - ROW infrastructure emissions for feeder (g/km-h)

$E_{v,t}$ - Feeder fleet manufacturing, operation & maintenance emissions (g/veh-km)

$E_{s,t}$ - Feeder station construction emissions (g/st-h)

Since transit demand is elastic, the mode shift from transit to automobile may incur auto emissions $E_{emissians,auta}$, in addition to the regular emissions of autos. The formula of $E_{emissians,auta}$ is taken from Griswold et al. (2014):

$$E_{emissians,auta} = \frac{L+W}{3} E_A D_A \tag{3.10}$$

E_A is the emissions parameter for automobile travel in units of GHG emissions per kilometer. D_A is the demand for auto travel in units of passengers per hour.

3.3 Hierarchy, demand elasticity and value of time

In this study, the transit demand is flexible in regard to three aspects:

(1) Demand shift between transit and automobile

(2) Demand split between transit and walking

(3) Demand split within the transit system: between trunk transit and feeder transit

The first aspect has been addressed in Griswold et al. (2014) for a trunk-only system by incorporating consumer surplus, and the third aspect has been addressed in Sivakumaran et al. (2014) by assuming a critical travel distance. We combine these two aspects of demand flexibility together and add the second aspect by assuming a critical walk-able distance.

The values of time differ for in-vehicle and out-of-vehicle travel times (Caltrans 2014). So it is necessary to monetize transit users' in- and out-of-vehicle travel time separately.

The Cobb-Douglas function is used to represent the demand for transit: $Q = aT_{l,verage}$, where a is a constant, $T_{average}$ is defined in Section 3.2.1, and bis the travel time elasticity for the Cobb-Douglas function. Since there is a different cost associated with in- versus out-of-vehicle travel time, we replace $T_{average}$ with a generalized cost (m):

$$m = \mu_{in} t_{in} + \mu_{aut} t_{aut} \tag{3.11}$$

$$Q = a \cdot m^b$$

t_{in} and t_{aut} are in- and out of vehicle travel times for a transit user:

$$t_{in} = \frac{(0.5r_i + 0.5r_w + s)}{2V_f} + (0.5r_i + 0.5r_w)\frac{L}{2S_t} + (L + W)\left(\frac{}{3V_t} + \frac{}{3s}\right) \tag{3.12}$$

$$t_{aut} = \frac{r}{V_a} + hr + H + T + 2T_{intra}$$

In order to convert C_{user} to unit of $/time, we set the constant a to be the transit demand density *p.*

The consumer surplus should be used when accounting for demand elasticity between transit and automobile (Daganzo, 2012). The updated definition of the cost to transit users and the consumer surplus are obtained from Griswold et al. (2014):

$$C_{user} = -consumer\ surplus \times LW \tag{3.13}$$

$$consumer\ surplus = \begin{cases} -pm_0 \ln\left(\frac{m}{m_0}\right) + canst & for\ b = -1 \\ \frac{pm_0 \left(\frac{m}{m_0}\right)^{b+1}}{b+1} + canst & otherwise \end{cases} \tag{3.14}$$

By adopting this new definition of C_{user} while keeping the rest of the terms in (3.1) unchanged, we are able to consider the demand shift between transit and automobile.

In order to consider the demand shift between transit and walking, and the demand shift between trunk transit and feeder transit, one could also define consumer surpluses as above and incorporate them in the model. However, this would significantly increase the complexity of the problem. Furthermore, studies suggest that the mode choice between transit and automobile is most significantly affected by transit travel time (other than factors such as transit fares), whereas the mode choice between walking and motorized modes (including transit) is most significantly affected by whether the trip is short enough to be walk-able (other than factors such as motorized travel time) (Frank et al. 2008, TRACE 1999). As a result, we assume that the demand split between transit and walking is determined by a critical walk-able distance, d_0.

Similarly, the demand split within the transit system (between the trunk transit and the feeder transit) is also addressed by using a critical travel distance (Sivakumaran et al. 2014), d_e.

It is reasonable to assume that $d_0 < d_e < L + W$.

Since the demand is assumed to be evenly distributed, the trip distance Z is a random variable. We define the portion of transit users that decide to only walk as P_w, the portion of transit users that decide to only use feeder system as P_1, and the portion of transit users that decide to use both feeder and trunk systems as P_t. According to the mode-choice principles defined in Section 3.1 and the discussions above, we have:

$$\begin{aligned} P_w + P_1 + P_t &= 1 \\ P_w &= \Pr(Z \le d_0) \\ P_1 &= \Pr(d_0 < Z \le d_e) \\ P_t &= \Pr(Z > d_e) \end{aligned} \tag{3.15}$$

We define the expected travel distance as below:

$$\begin{aligned} d_w &= E(Z|Z \le d_0) \\ d_t &= E(Z|d_0 < Z \le d_e) \end{aligned} \tag{3.16}$$

$$d_t = \mathrm{E}(Z|Z > d_c)$$

The formula for calculating the expected travel distance is derived and described in Appendix A. The definition of m is then updated by dividing the transit users into three groups and obtaining the weighted sum.

$$m = \mu_{in}\left(P_f t_{in,f} + P_t t_{in,t}\right) + \mu_{out}\left(P_w t_{out,w} + P_f t_{out,f} + P_t t_{out,t}\right) \quad (3.17)$$

Where,

$$t_{in,f} = \frac{d_f}{v_f} + \frac{d_f r_f}{s_f} + \frac{d_f}{0.5rL + 0.5rw}\frac{s}{2v_f}$$

$$t_{in,t} = \frac{d_t}{v_t} + \frac{d_t r_T}{s} + (0.5rL + 0.5rw + s)\frac{1}{2} + (0.5rL + 0.5rw)\frac{r_f}{2}$$

$$t_{out,w} = \frac{d_w}{v_a} \quad (3.18)$$

$$t_{out,f} = \frac{r_f}{v_a} + h_f$$

$$t_{out,t} = \frac{r_T}{v_a} + h_T + H + T + 2T_{intra}$$

$t_{in,f}$ is the average in-vehicle travel time for the P_f portion of transit users. It consists of the expected cruising travel time $\left(\frac{d_f}{v_f}\right)$, the average lost time due to dwelling at feeder stops $\left(\frac{d_f r_f}{s_f}\right)$, and the average lost time due to detouring to the trunk station according to the structure of our hierarchical network. The average number of detours of length $\frac{s}{2}$ is $\frac{d_f}{0.5rL+0.5rw}$, so the average detouring time is $\left(\frac{d_f}{0.5rL+0.5rw}\frac{s}{2v_f}\right)$.

$t_{in,t}$ is the average in-vehicle travel time for the P_t portion of transit users. It consists of the expected cruising travel time in trunk system $\left(\frac{d_t}{v_t}\right)$, the average lost time due to dwelling at trunk stops $\left(\frac{d_t r_T}{s}\right)$ and the average time spent in feeder system in order to access trunk, including the feeder cruising time $\left((0.5rL + 0.5rw + s)\frac{1}{2v_f}\right)$ and the feeder dwelling time $\left((0.5rL + 0.5rw)\frac{r_f}{2s_f}\right)$.

$t_{out,w}$ is the average out-of-vehicle travel time for the P_w portion of transit users, which is the same as the walking time for travelling expected distance d_w.

$t_{out,f}$ and $t_{out,t}$ are the average out-of-vehicle travel times for the P_f and P_t portions of transit users respectively. Both of them have the terms of average time spent walking to and waiting for feeder transit $(\frac{1}{v_a} + hr)$, while users that also use trunk transit incur an additional travel time from waiting for trunk transit (H), transferring within trunk transit *(T),* and transferring between feeder and trunk transit *(2Tintra)-*

In summary, the general formulation (3.1) is specified by (3.4)-(3.10), (3.13), (3.14), (3.15)-(3.18).

Chapter 4 Parametric Study

This chapter describes the process of employing the optimization model defined in Section 3.2 and 3.3 through a parametric study. In Section 4.1, values are assigned to the parameters in the model based on four scenarios. The results obtained after plugging these values in the optimization model are presented in Section 4.2 and Section 4.3.

4.1 Scenarios, mode attributes, cost and emissions factors

To provide insights from the idealized network described above, it is necessary to adjust the model attributes as close as possible to the attributes ofreal cities. Four hypothetical scenarios are employed to roughly categorize real cities with varying sizes and demand densities (Table 4.1). The scenarios are obtained from Griswold et al. (2013).

Table 4.1 City scenarios with different combinations of sizes and demand densities Griswold et al. 2013)

	City size (L, W) (km)		Demand density (p) (pax/km^2/h)	
Scenario 1	Small	10	Low	100
Scenario 2	Small	10	High	200
Scenario 3	Large	40	Low	100
Scenario 4	Large	40	High	200

The user values of time for in- and out-of-vehicle travel time are \$12.5/h and \$25/h respectively, taken from California Department of Transportation (Caltrans) (2012). The critical distances d_0 and *de* are assumed to be 400 m and 4 km respectively. Mode attributes, costs and emissions factors for the trunk transit are obtained from Griswold et al. (2014), where four different trunk transit technologies (bus, BRT, LRT or metro) are considered (Table 4.2). The costs and emissions of trunk transit modes, except for bus which is generally diesel, are modeled after systems in the San Francisco Bay Area: BRT is based on the proposed design for the Geary Boulevard BRT and LRT on the Muni light rail system, metro is based on the Bay Area Rapid Transit (BART) system. For these trunk and feeder modes, the non-operational emissions estimates (infrastructure construction and maintenance, vehicle manufacture and maintenance) and operational emissions estimates are adopted from Chester and Horvath (2009) and Chester (2008), where a hybrid life-cycle-assessment model was employed and the Californian electricity mix was used. The emission factor for bus operation is taken from Taptich and Horvath (2014), and EMFAC (CARB 2014) data are also incorporated in this work to allow for more updated emissions estimates.

Table 4.2 Trunk-mode-specific model parameters[1] (Griswold et al. 2014)

Param	Description	Units	Bus	BRT	LRT	Metro
v	Cruising speed	km/h	25	40	40	60
τ	Lost time/stop	sec.	30	30	30	45
T	Lost time/transfer	sec.	20	30	30	60
$C1$	ROW infrastructure cost	\$/km-h	10	36	220	260
Cv	Vehicle purchase, fuel & maintenance cost	\$/veh-km	1.0	1.6	6.0	8.9
CM	Labor cost	\$/veh-h	150	200	200	250
Cs	Station construction cost	\$/st-h	0.82	8.2	11	130
$E1$	ROW infrastructure emissions	g/km-h	8.1	160	790	44,000
Ev	Vehicle fleet manufacturing, operation & maintenance emissions	g/veh- km	1,445	1,900	2,700	11,000
Es	Station construction emissions	g/st-h	170	1,700	1,700	120,000
Kap	Vehicle capacity	pax/veh	80	120	200	1000

[1]The EMFAC database provides emission factors for buses and are more recent than those in Chester and Horvath (2009) and Chester (2008). Thus compared with the table in Griswold et al. (2014), I update the emission factor Ev for bus from 1,700 g/veh-km to 1,445 g/veh-km, and the emission factor Ev for BRT from 2,200 g/veh to 1,900 g/veh-km.

For the feeder transit system, we consider only one mode: feeder bus (usually smaller buses or vans designed mainly for local service).

The feeder-mode cost parameters are calculated based on the parameters of regular bus for the trunk transit, since the usual feeder bus is the bus of smaller size compared to the trunk bus. We assume all the cost parameters for the feeder mode to be 80% of the corresponding values for the trunk bus, and cruising speed to be 20 km/h with dwelling time lost at each feeder stop to be 20 s (Sivakumaran et al. 2014). Emissions parameters for the feeder mode are estimated from Chester and Horvath (2009) and Chester (2008). All the parameters for the feeder mode are listed in Table 4.3.

Table 4.3 Feeder-mode-specific model parameters

Param	Description	Units	Feeder bus
v	Cruising speed of feeder	km/h	20
τ	Lost time/feeder stop	sec.	20
C_{lJ}	ROW infrastructure cost for feeder	$/km-h	0
C_{vJ}	Feeder purchase, fuel & maintenance cost	$/veh-km	0.8
C_M	Feeder labor cost	$/veh-h	120
C_s	Feeder station construction cost	$/st-h	0.66
E_{lJ}	ROW infrastructure emissions for feeder	g/km-h	0
E_{vJ}	Feeder fleet manufacturing , operation & maintenance emissions	g/veh-km	1,360
E_{sJ}	Feeder station construction emissions	g/st-h	136
Kap	Vehicle capacity	pax/veh	60

Here we assume the right-of-way (ROW) infrastructure cost and emissions for feeder systems are all (approximately) zero because the feeder bus often operates on already-existing roads and we optimize their routes based on these exiting micro-networks. The feeder system optimization won't cause new road construction, thus those parameters are assumed to be zero.

4.2 Non-elastic case

After assigning values for the model attributes, Pareto curves showing the relationships between E and C_{total} are developed for the different scenarios, and for the four trunk technologies (bus, BRT, LRT or metro) with the feeder access. The Pareto curves for the trunk-only bus systems are also developed to compare with the hierarchical transit systems. In this section, we assume that the total transit demand is inelastic for the entire transit system, i.e., $b = 0$. Particularly, the transit system will be serving a constant number of transit users not matter how much the transit LOS has changed. This is a rather optimistic case because it implies that lowering the transit LOS would not motivate transit users to switch to the automobile, hence there is no incremental auto emissions, and the total emissions savings would equal to the net "gain" of the transit emissions reduction efforts.

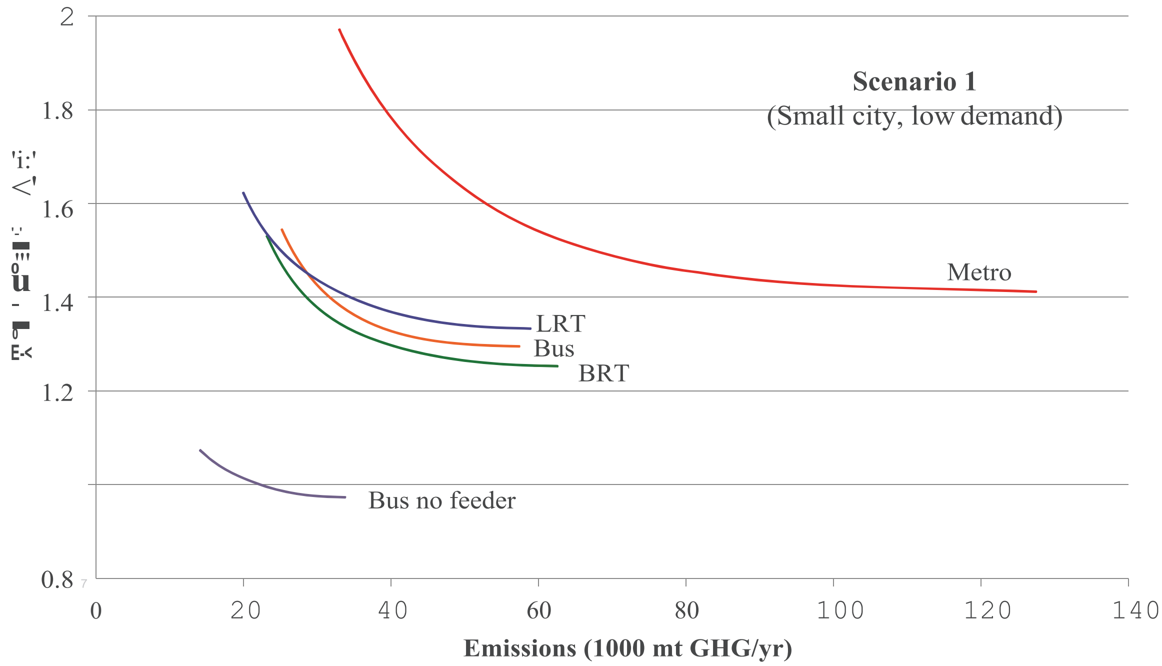


Figure 4.1 Technology-specific Pareto curves of system costs with varying transit emissions (scenario 1)

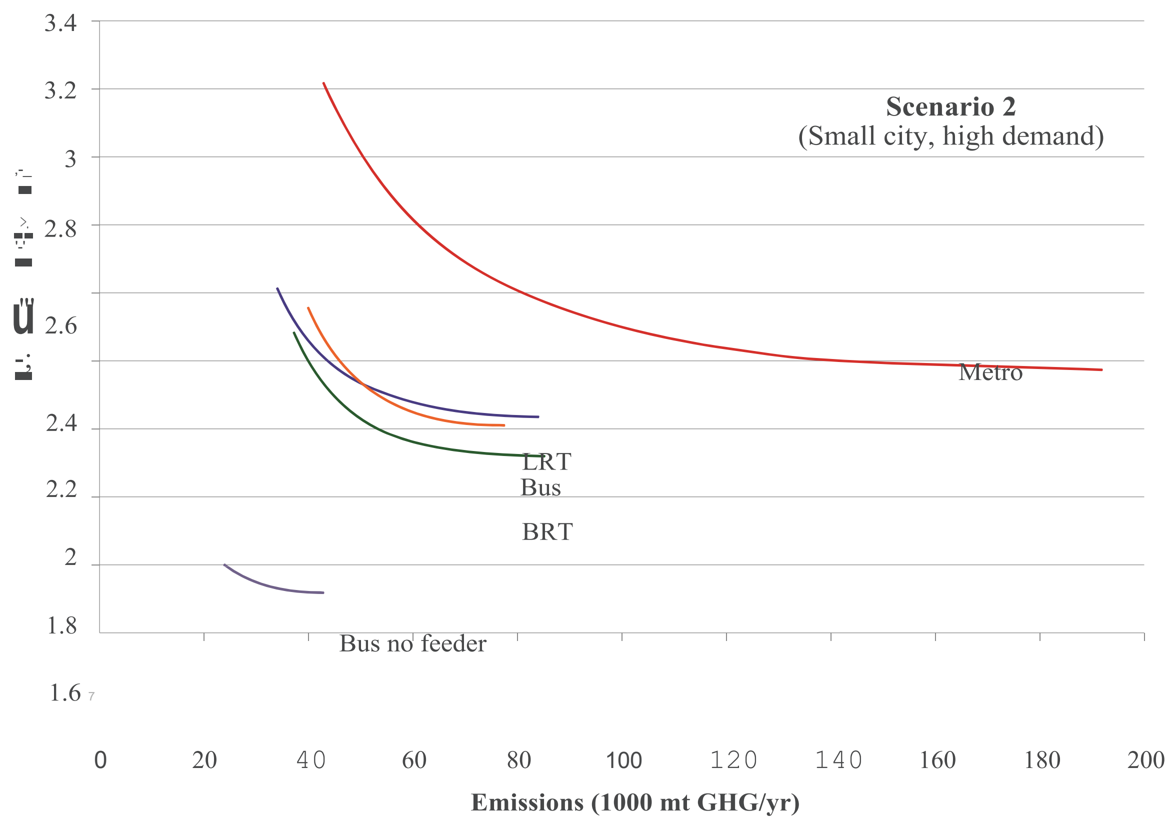


Figure 4.2 Technology-specific Pareto curves of system costs with varying transit emissions

(scenario 2)

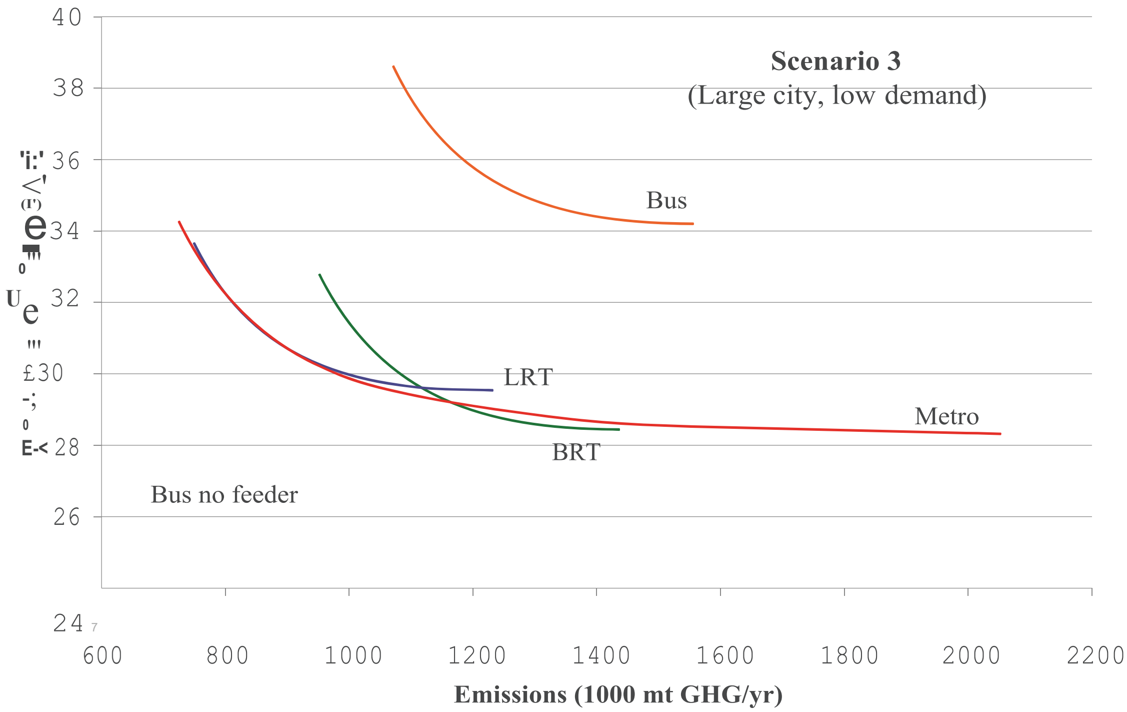


Figure 4.3 Technology-specific Pareto curves of system costs with varying transit emissions (scenario 3)

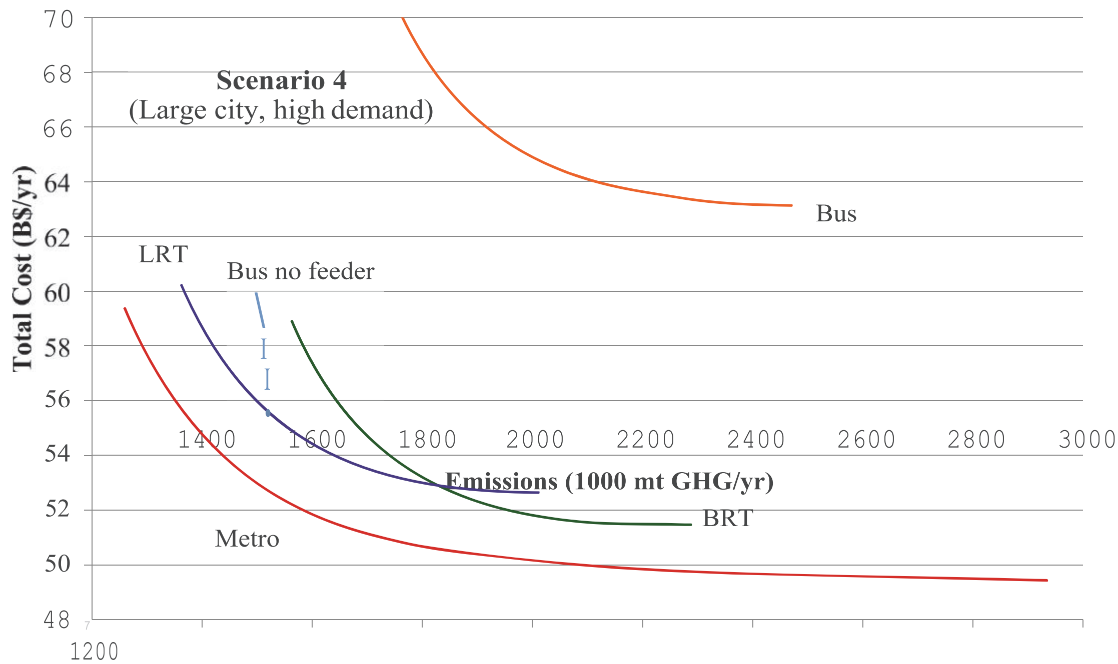


Figure 4.4 Technology-specific Pareto curves of system costs with varying transit emissions (scenario 4)

Figure 4.1 shows the Pareto curves for optimal transit system design by different trunk technologies for a small city with low demand (scenario 1). Compared with all the hierarchical transit systems, bus with no feeder access is the lowest-cost option for all values of the GHG emissions constraint. This is because the average travel distances are short for small cities, which eliminates the relative disadvantage of low cruising speeds of buses compared with the other modes. Furthermore, the low infrastructure cost of a bus network allows for smaller stop and route spacings, alleviating the need for incorporating the feeder access. The intra-modal transfer times and feeder emissions are avoided as a consequence. Among the hierarchical transit systems, BRT is the lowest-cost option for all values of the GHG emissions constraint. However, LRT and buses have lower GHG emissions than BRT at their respective cost-optimal points. For cities similar to scenario 1 that aim to optimize only transit system costs, LRT or buses are better than BRT in reducing GHG emissions. Metro is not a competitive option in this context because its costs are higher than all the other modes for all values of the GHG emissions constraint. Moreover, metro has the highest GHG emissions at its cost-optimal point compared with all the other modes. For these hierarchical transit systems, the order of preference for the trunk technologies is consistent with the results of Griswold et al. (2013), where the feeder access is not provided. In summary, incorporating feeder access does not significantly change the comparisons between the trunk technologies for scenario 1, and the societal costs and emissions are even much higher compared with the trunk-only bus system.

With the transit demand being doubled (Figure 4.2, scenario 2), the transit agency must improve the service level to minimize the societal cost. The emissions increase for all modes due to the improved LOS, along with the increased societal costs, due to the higher demand. Nevertheless, bus with no feeder access is still the lowest-cost option for all values of the GHG emissions constraint.

As for the large cities, the average travel distances are longer, making metro more cost-competitive due to its higher cruising speed (by reducing travel time). Furthermore, incorporating the feeder access allows for larger stop and route spacings, saving the agency cost significantly by requiring a lower amount of the expensive metro infrastructure. This can be verified in Figures 4.3 and 4.4, where metro is the lowest-cost option for most values of the GHG emissions constraint. Buses are the worst choice in this context due to high costs for all values of the GHG emissions constraint. The shortcoming of buses includes low cruising speeds magnified by long average travel distances in large cities, increasing travel time significantly. Meanwhile, the low capacity of buses requires a larger fleet of buses to cover all the transit demand, which also results in a significant increase in agency cost in this large-city scenario. LRT and BRT are better than buses but less cost-competitive than metro, yet both have lower GHG emissions than metro at their respective cost-optimal points. Although the GHG emissions associated with metro are high at the cost-optimal point, these emissions can be significantly reduced without causing large additional societal costs. Take scenario 3, for example, the GHG emissions of metro can be reduced by 30% from 2051 mt GHG/yr to 1435 mt GHG/yr, with only a 2% increment in the societal cost from $28.3 billion per year to $28.8 billion per year. Moreover, in scenario 4, metro is the lowest-cost option for all values of the GHG emissions constraint.

It should be noted that in generating the Pareto curves of the trunk-only bus system in the large cities (scenario 3 and 4), we find that the cost-optimal point is bound by the bus capacity constraint, which means the buses are already fully loaded in order to cover all the transit demand. With the binding capacity constraint, emissions cannot be reduced any further because that is achieved through lowering the operational frequency and spatial coverage, which will result in bus overloading (the same transit demand is covered by decreased bus service). As a result, the Pareto curve is essentially limited to the cost-optimal point, which can be observed in Figures 4.3 and 4.4. For the hierarchical bus system, we find that the bus capacity constraint is also binding at the cost-optimal point in both scenarios. However, the Pareto curves are not limited to the cost-optimal points because the emissions can still be reduced from the feeder system. We also find that the capacity constraint for the feeder system is not binding because the service area for each feeder bus is small.

4.3 Elastic case

In this section, we consider the potential demand shift between transit and automobile, where some transit users may switch to automobile when the transit LOS is reduced, i.e. b is non-zero. To examine how the GHG emissions are affected by the changed demand due to the reductions in service, curves showing the relationships between the total GHG emissions $(E_{emissions,T} + E_{emissions,auto})$ and total transit travel time $(T_{average})$ are developed for different trunk technologies. $E_{emissions,auto}$ denotes the marginal automobile emissions due to users switching from transit to cars.

Previous research has established a range of reasonable travel time elasticity values for transit in major U.S. cities (Griswold et al. 2014), hence the value of b may differ for different scenarios and trunk technologies. To account for this variability, I examine the impact of b between 0.0 and -1.0 on the E - T curves.

We base the elastic case on scenario 2 (small city with high demand), a hypothetical city with characteristics similar to San Francisco.

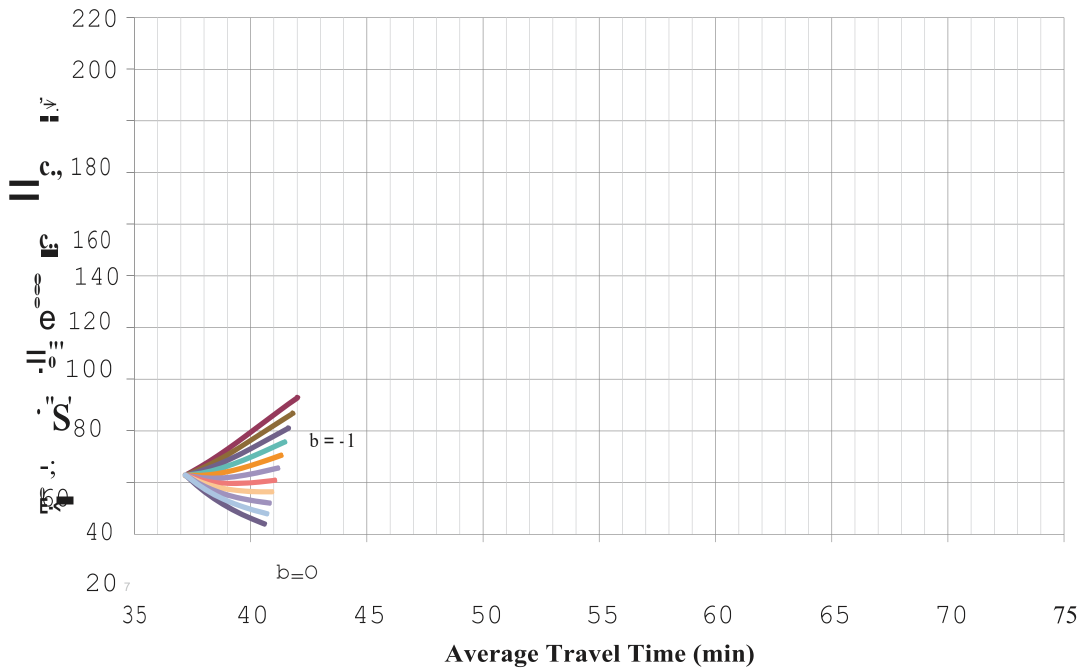


Figure 4.5 Change in **total emissions with travel time as LOS** is **reduced for bus with no feeder access (scenario 2)**

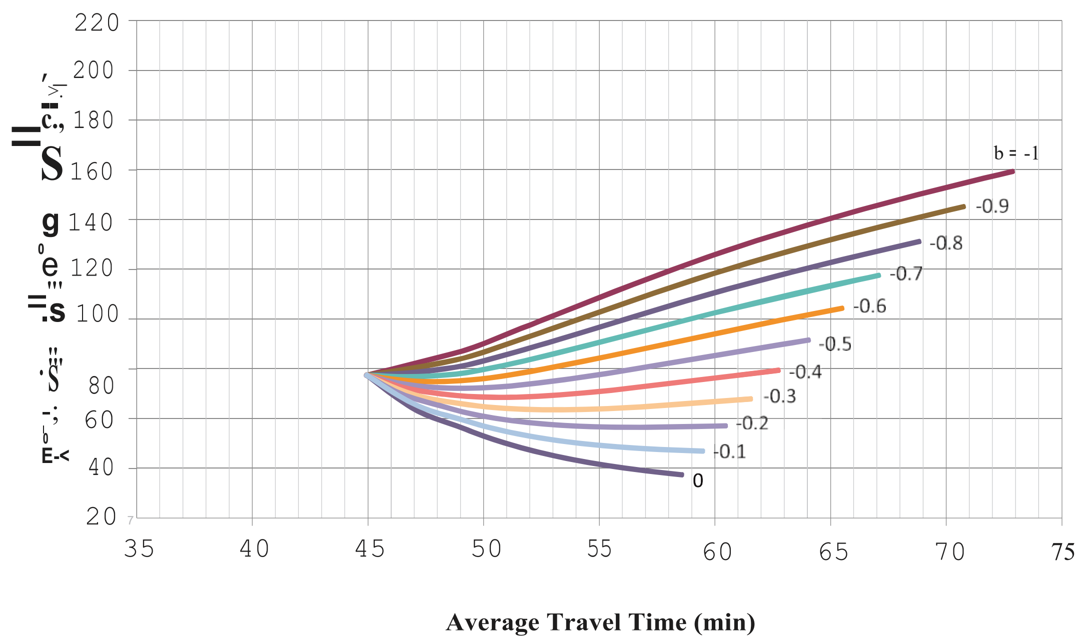


Figure 4.6 Change in total emissions with travel time as LOS is reduced for bus (scenario 2)

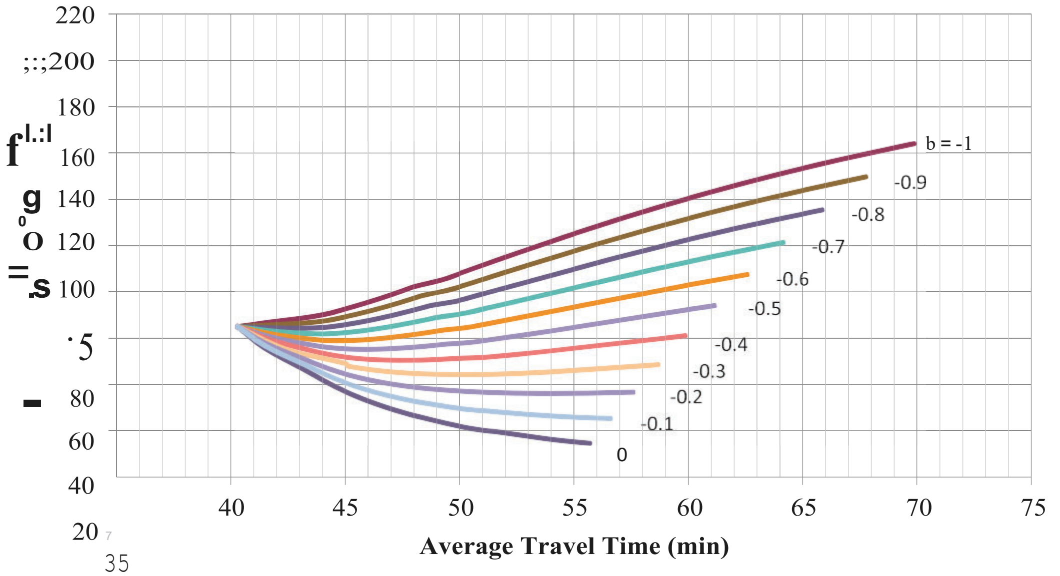


Figure 4.7 Change in total emissions with travel time as LOS is reduced for BRT (scenario 2)

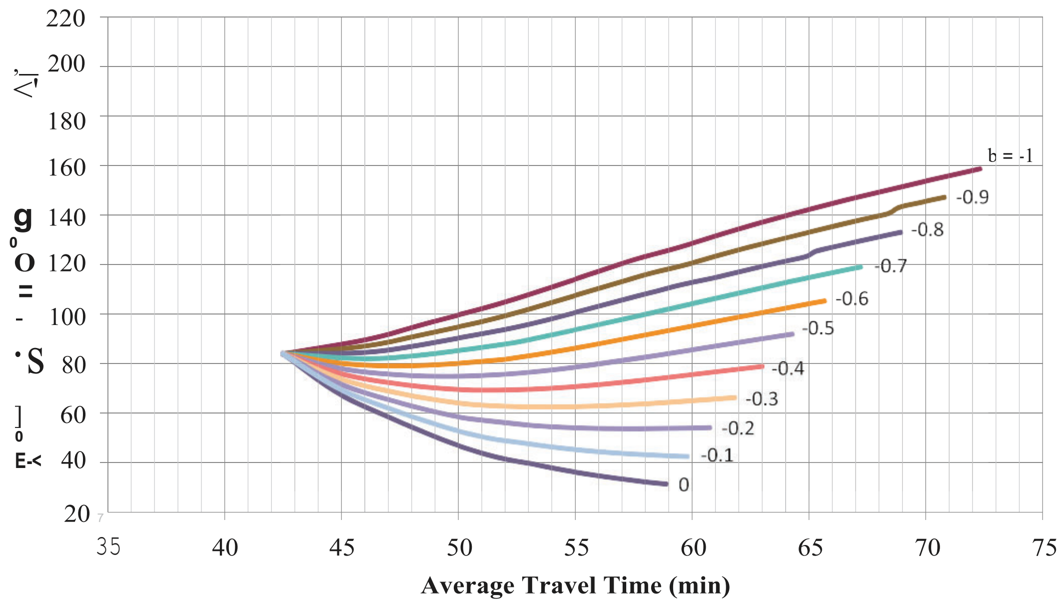


Figure 4.8 Change in total emissions with travel time as LOS is reduced for LRT (scenario 2)

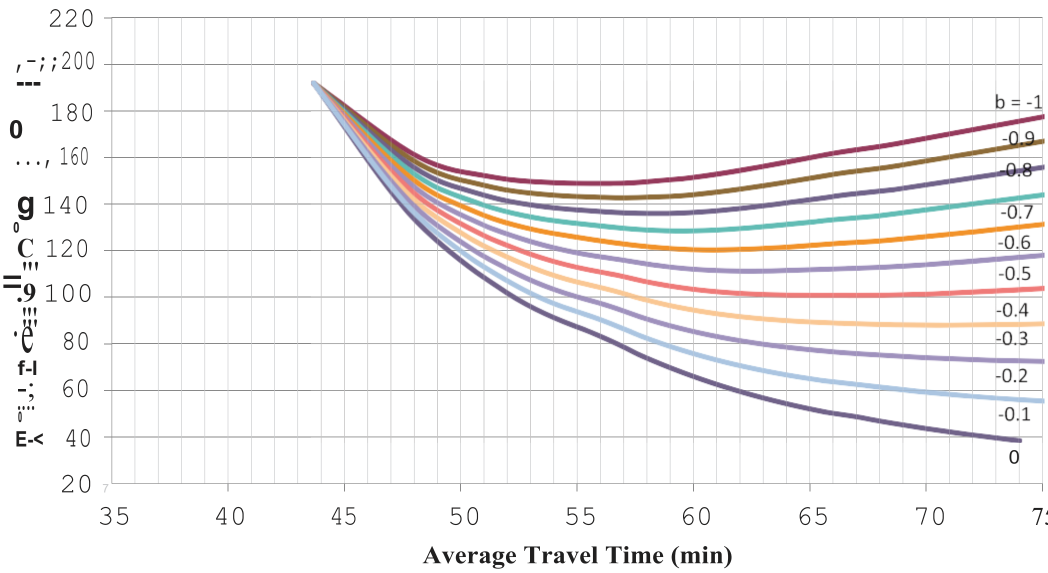


Figure 4.9 Change in total emissions with travel time as LOS is reduced for metro (scenario 2)

Figures 4.5 through 4.9 show the change in total GHG emissions as transit travel time is increased from the cost-optimal value for a range of travel time elasticities. The figures are each shown with the same scale on the horizontal and vertical axes to allow for visual comparison. The bottom line (b = 0) shows the results for inelastic demand, where no users will change modes when the transit travel time increases (as a result of the reduced transit LOS). The top line (b = -1) shows the results where users are most sensitive to changes in the transit travel time.

In the case of the trunk-only bus system (Figure 4.5), the elasticity values between -0.8 and -1 produce monotonically increasing emissions as the travel time increases from the cost-optimal value, implying that slight LOS reductions for a city with highly elastic transit demand would be harmful to both the transit users and the emissions. When the elasticity values are between -0.6 and -0.7, there is initially a small emissions benefit as the transit LOS is lowered. However, as the transit travel time approaches 39 min, the emissions start to increase. The elasticity values between O and -0.3 produce monotonically decreasing emissions. The elasticity values between -0.4 and -0.5 produce slight or no emissions reductions over the travel time values shown. Nevertheless, the trunk-only bus system is still competitive for both emissions and travel time, compared with all the other hierarchical transit systems in scenario 2.

The case of the hierarchical transit systems (Figures 4.6 through 4.9) shows the similar relationship between the total emissions and the travel time as in Figure 4.5. I find that, for buses, BRT and LRT, the elasticity values between -0.6 and -1 all produce increases in emissions over the travel time values shown. Thus for cities with highly elastic transit demand, transit systems with these trunk technologies should be designed near the cost-optimal points. However, greater reductions in the total GHG emissions are possible for low to moderate elasticities. In the case of metro (Figure 4.9), the emissions reductions are possible for all the elasticity values. The reductions are especially significant as the LOS is lowered from the cost-optimal value.

In summary, since the emissions constraint is imposed on the transit systems alone, we have verified that unintended consequences (increases in the city-wide emissions as a result of LOS reductions) will occur for highly elastic transit riders or for large reductions in transit LOS. However, these consequences are less likely in the case of metro. As a result, a metro system does not need to be designed near the cost-optimal point.

The previous discussions are based on the formulation (3.1) where the emissions constraint is imposed on the transit system alone. As was shown above, this could lead to the unintended consequence of city-wide emissions increasing as we impose the transit emissions constraint.

Next, we study the elastic case based on a small city (scenario 2) emissions budget, where the emissions constraint is imposed on the entire city rather than only on the transit system, as shown in (4.1).

$$\begin{aligned} \min \quad & C_{total} = C_{user} + C_{agency} \\ s.t. \quad & E_{emissions,T} + E_{emissions,auto} \leq E \\ & Load \leq Kap \end{aligned} \tag{4.1}$$

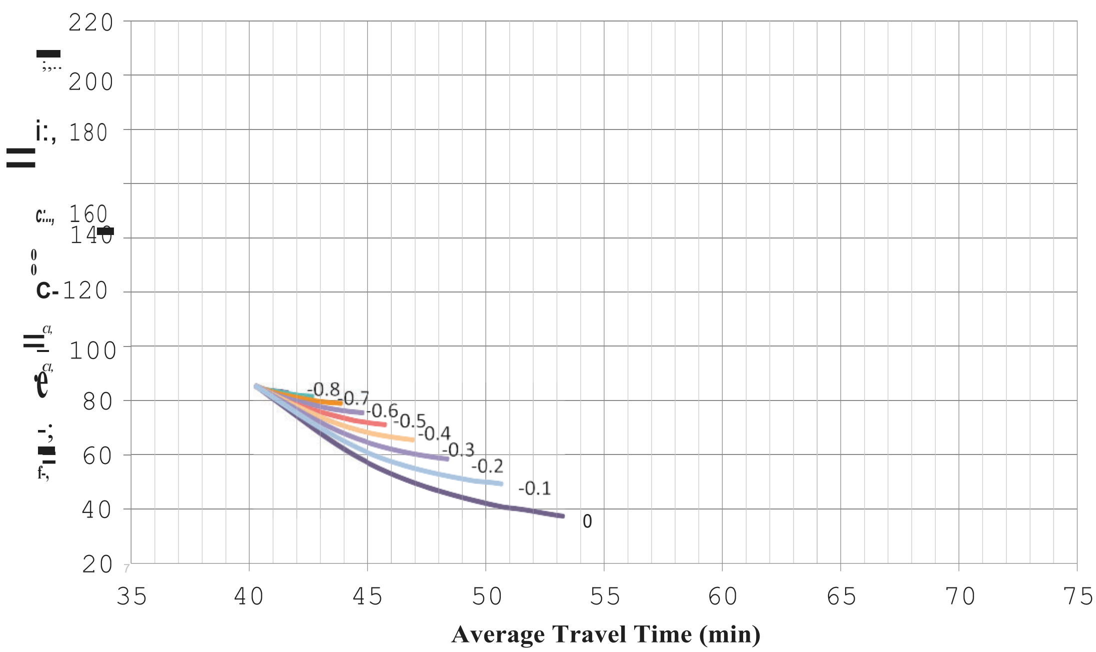


Figure 4.10 Change in total emissions as LOS is reduced for BRT under a city-wide emissions budget (scenario 2)

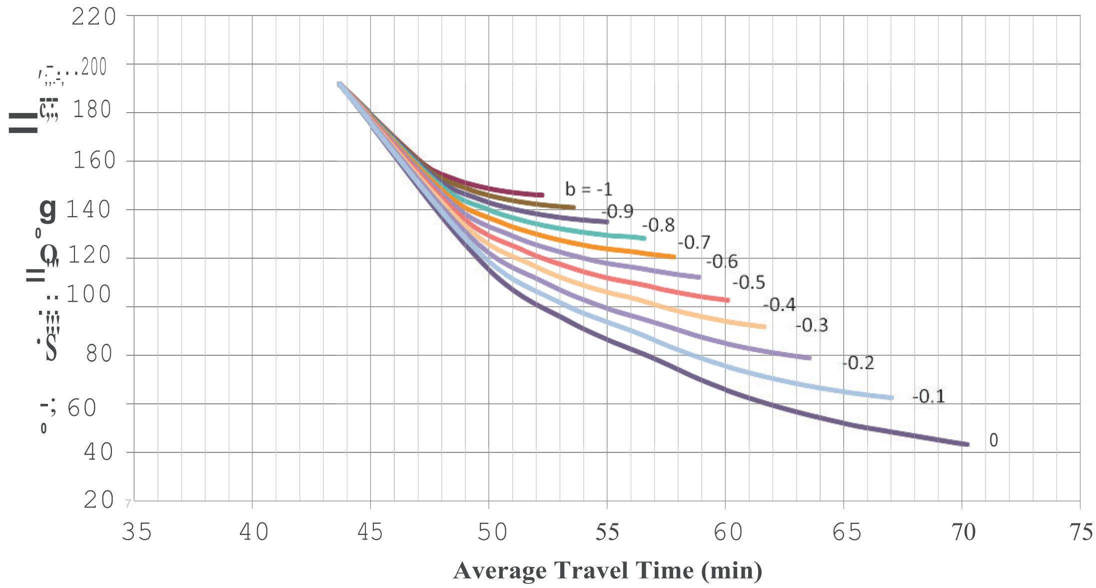


Figure 4.11 Change in total emissions as LOS is reduced for metro under a city-wide emissions budget (scenario 2)

Figures 4.10 and 4.11 show the results of this city-scale optimization for BRT and metro. The results for bus and LRT are similar to BRT and thus are not shown here. Increases in total emissions are avoided because they are constrained by E in (4.1). Compared with Figures 4.7 and 4.9, the curves are truncated at the points where it is no longer possible to reduce the total emissions. These points represent the states where further reductions in transit emissions start to be overtaken by the increases in automobile emissions. For the case of the BRT system, the reductions in total emissions are not possible for high elasticity values, which is consistent with Figure 4.7. As a result, the curves of $b = -1$ and $b = -0.9$ are negligible. For the metro system, the reductions in total emissions are possible for all the values of elasticity.

4.4 Effect of city size on emissions

In the previous section we studied the elastic case for a small city (scenario 2), and verified that for hierarchical metro systems, there exists a phase of decreasing total emissions as LOS is lowered, even for highly elastic transit demand. However, this is not necessarily true for larger cities where automobile emissions are much higher due to the longer average driving distance. To verify this conjecture, we study the metro system for a large city (scenario 4) in this section.

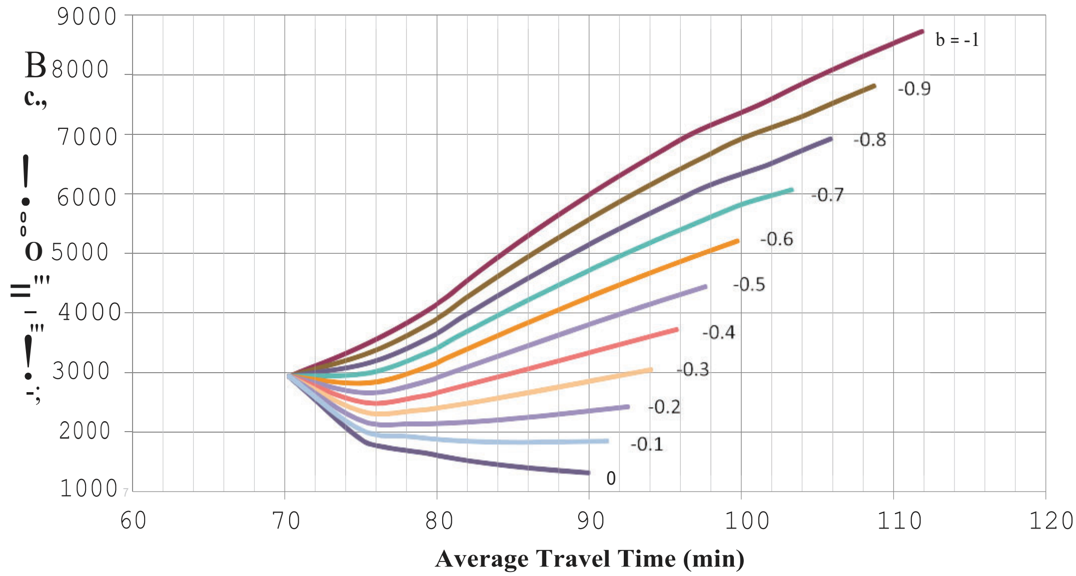
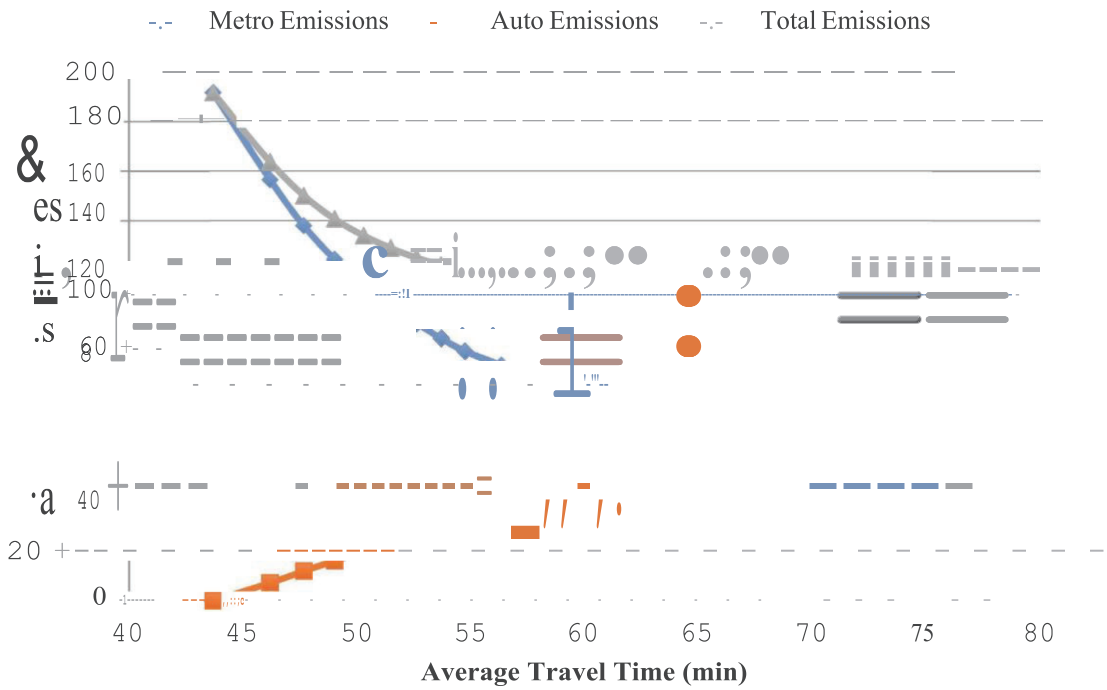
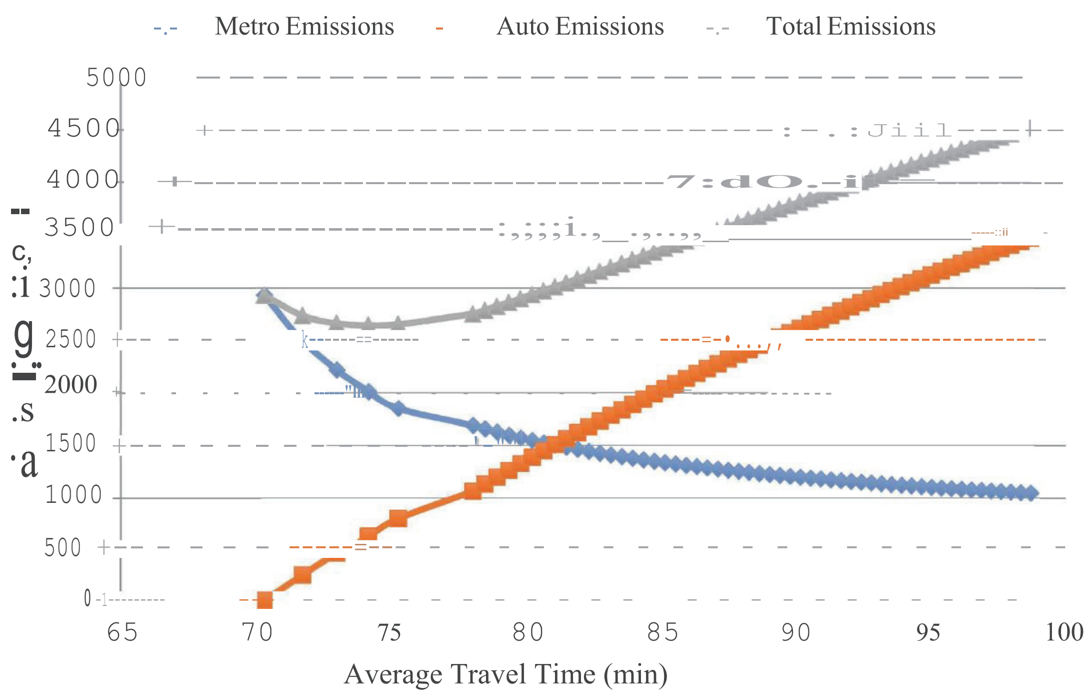


Figure 4.12 Change in total emissions as LOS is reduced for metro (scenario 2)

Figure 4.12 shows the relationship between the total emissions and LOS for a large city (scenario 4). Compared with Figure 4.9, it is easy to observe the difference: with high elasticity, $b = -1$ for example, the total emissions increase monotonically as the LOS is lowered from the cost-optimal point. The situation is similar for middle elasticity, $b = -0.5$ for example, where the potential reduction in total emissions is negligible. As a result, for a large city with elastic metro demand, it is not recommended to lower the metro LOS for the sake of reducing the emissions. The underlying reason is that when the city size increases, the average driving distance also increases. These longer distances lead to significantly higher auto emissions. As the metro LOS is lowered, large auto emissions are generated as transit users shift to the automobile, completely overtaking the reductions in metro emissions. Figure 4.13 shows the breakdown of the total emissions where we can see the difference between the small city and the large city scenarios.



(a)



(b)

Figure 4.13 Breakdown of the total emissions of metro *(b* = -0.5)

(a) scenario 2; (b) scenario 4

The dominance of auto emissions for the case of a large city means that large cities should rely more on transit in order to reduce emissions. Figure 4.14 shows the two extremes, where cities with varying sizes rely either on automobile or metro to cover the entire demand. As an auto-only city expands, the emissions increase dramatically due to the longer average driving distance and larger demand. For a city that runs on transit, the emissions also increase as a higher transit frequency is required. However, transit generates much lower emissions than automobile especially for large cities.

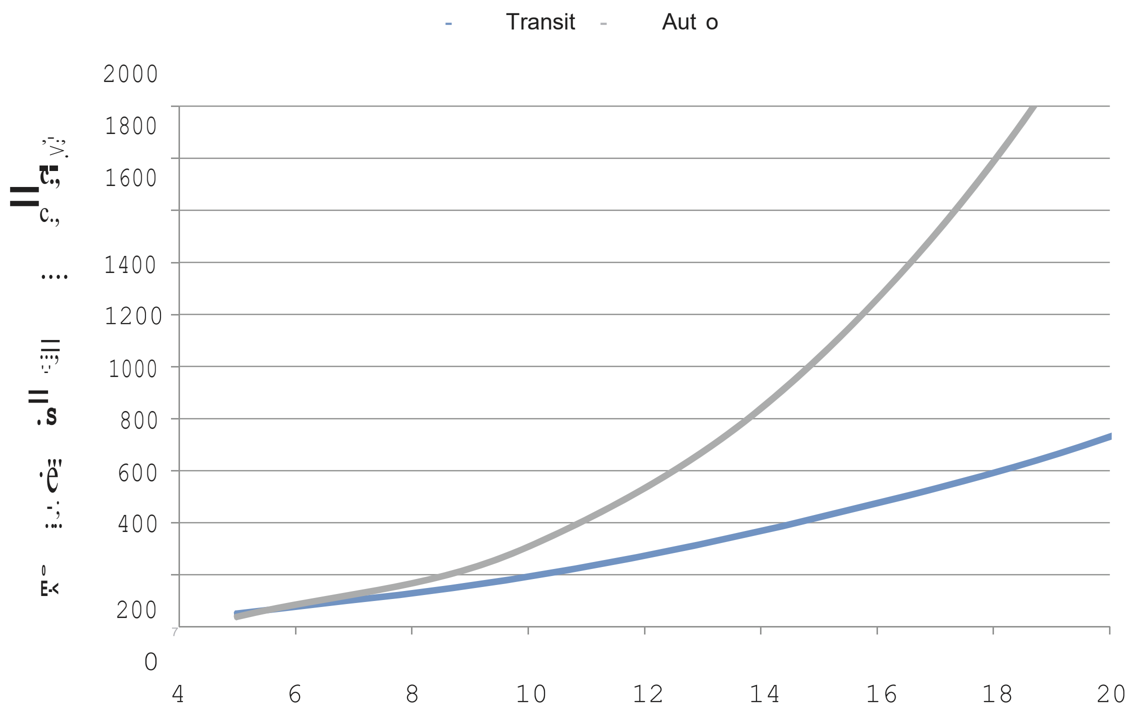


Figure 4.14 Total emissions of city with varying size

4.5 Sensitivity Analysis

Admittedly, the mode attributes, cost and emission factors for the trunk transit and feeder transit used in this study may vary in different cities and time windows. This has the potential of shifting the Pareto curves and affecting the comparisons of transit technologies. The changed parameters may also alter the shape of the curves in Figures 4.5 through 4.11 hence affecting the discussion on elasticity. A set of sensitivity analyses has been conducted to address these concerns. The analyses help us evaluate the robustness of our conclusions to parameter uncertainties.

For example, Figure 4.15 shows the Pareto curves of metro, BRT and trunk-only bus for scenario 2 after all the parameters are changed by ±30%. Table 4.3 shows an example of parameter changes for metro trunk in sensitivity analysis. The solid curves refer to those in Figure 4.2 where the parameters were not changed. It should be noted that ±30% refers to the extreme cases where all the parameter changes contribute in the same direction to the changes in costs or emissions. In the real world, the contributions from different parameter changes often cancel out each other, and thus the Pareto curves are located between the boundaries provided in the extreme cases (Figure 4.15). It can be observed that the position of the Pareto curves is of low sensitivity to the changes in the parameters. The shifted curves may affect the comparisons of BRT, LRT and bus due to the closeness between them in Figure 4.2. However, the advantage of trunk-only bus and the inferiority of metro remains obvious as in Figure 4.2.

Table 4.4 Parameter changes for metro trunk in sensitivity analysis

Param	Description	Units	-30%	-20%	-10%	0	10%	20%	30%
C,	ROW infrastructure cost	$/km-h	182	208	234	**260**	286	312	338
Cv	Vehicle purchase, fuel & maintenance cost	$/veh-km	6.23	7.12	8.01	**8.9**	9.79	10.68	11.57
CM	Labor cost	$/veh-h	175	200	225	**250**	275	300	325
Cs	Station construction cost	$/st-h	91	104	117	**130**	143	156	169
E,	ROW infrastructure emissions	g/km-h	30,800	35,200	39,600	**44,000**	48,400	52,800	57,200
Ev	Vehicle fleet manufacturing, operation & maintenance emissions	g/veh-km	7,700	8,800	9,900	**11,000**	12,100	13,200	14,300
Es	Station construction em1ss10ns	g/st-h	84,000	96,000	108,000	**120,000**	132,000	144,000	156,000

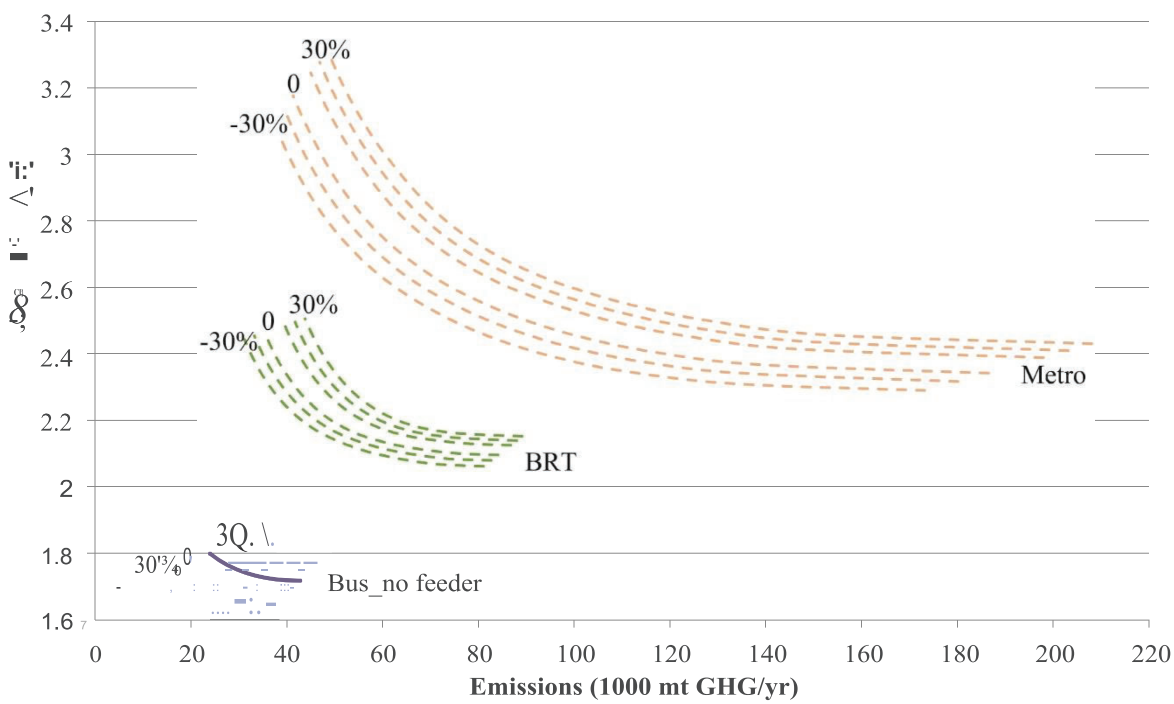


Figure 4.15 Sensitivity to changes in parameters for metro, BRT and trunk-only bus (scenario 2)

Similar observations are made for scenario 1, 3 and 4. It is also observed that the changes in the parameters slightly modifies the positions of the curve clusters in Figures 4.5 through 4.11. However, the shapes of the curves remain the same. Since the discussion on elasticity is largely based on the curve shapes, it is insensitive to the parameter changes.

Chapter 5 Implementation: Transit Network Stylization

In the previous chapters, we analyzed various hypothetical city scenarios and quantified the emissions saved when reducing the transit LOS. The model in those scenarios utilized an idealized rectangular grid transit network. We used continuum approximation (CA) method to minimize the societal costs subject to an emissions constraint, identifying the Pareto curve of optimal transit system design.

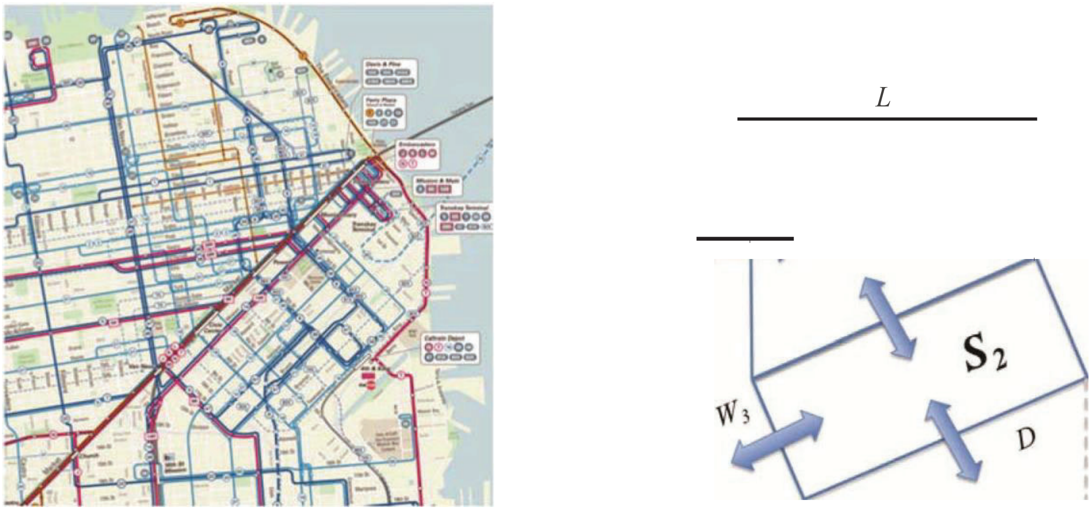
In reality, most current transit systems have not been optimized to achieve the lowest costs and emissions possible. Therefore, they do not necessarily fall on the Pareto curve. In this chapter, we extend the model to analyze such a transit system, the MUNI bus network for the city of San Francisco. We build a mathematical model of the MUNI bus network to obtain a relatively accurate representation of the current network. We quantify the societal costs and emissions for the current MUNI system, and where it falls relative to the Pareto curve. The potentials for emissions reductions and the changes in LOS are then discussed for the MUNI system.

As in our previous model, the continuum approximation method is employed to derive the costs and the emissions of the transit system. Since the method requires networks with simple geometric patterns, we choose a stylized network to approximate the real MUNI network. The stylization procedure is described in section 5.1. The evaluation of the stylized network is presented in section 5.2. Based on the stylized network, the optimal bus system attributes are selected, which are discussed in detail in Chapter 6.

5.1 Network stylization

Transit networks are often irregular in shapes. They are confined by the geographical layout of real cities. To use the continuum approximation method, it is necessary to stylize the complex network to the form of its closest geometric idealization. Figure 5.1 shows the network of downtown San Francisco Muni bus system in real shape (a) and after stylization (b). Note that for simplicity, only the downtown portion of the Muni network is considered.

The downtown area can be stylized as a combination of one trapezoid area and one rectangle area overlapping at an edge, Market Street. The other edges serve as the boundary of the area of interest in this case study (Table 5.1). Since the bus network in the downtown area is of grid structure ubiquitously (Figure 5.1 (a)), we define a stylized grid structure within the boundary (Figure 5.1 (b)). Within the trapezoid and rectangle, the bus routes are aligned orthogonally to maintain the grid feature. The stop spacing (s) and route spacing *(r)* are assumed to be the same throughout the network to filter out the complex network details.



(a) (b)

Figure 5.1 San Francisco Muni system

(a) The network of downtown San Francisco Muni system (SFMTA 2016)
(b) The stylization of the network in the San Francisco downtown area.

Table 5.1 Boundary of the studied area

Edge	Street Name
L	Bay Street
W_2	Van Ness Avenue
W_3	11th Street
D	Harrison Street
W_1	The Embarcadero

Admittedly, stylization may bring in some errors due to possible oversimplification of the real network. To evaluate the influence of the stylization, it is necessary to compare the costs and emissions derived from the stylized network with those of the real network. The evaluation is provided in section 5.2.

5.1.1 Derivation of the user costs

The continuum approximation method is used in the derivation of the costs and emissions from the stylized network. The method enables us to formulate costs and emissions as closed-form functions of basic system attributes. In this study, the attributes consist of i) supply-side parameters: stop spacing (s), route spacing (r), and headways (H); ii) demand-side parameters: demand density (p), value of time (μ). The detailed derivations of these costs and emissions are described below.

The cost to a transit user is measured by the time spent using the transit service. The user cost C_{user} is the sum of costs to all the transit users. The transit demand is divided into several categories to account for different O-D scenarios (Table 5.2). Similar to the previous chapters, since the values of the time spent in- and out of transit vehicles are different (Caltrans 2014), it is necessary to derive separately the in-vehicle travel time (IVTT) and the out of vehicle travel time (OVTT). The user cost *Cuser* is therefore formulated as the sum of monetized IVTT and OVTT for different categories (5.1).

$$Cuser = \sum_{(a,b)\in G} (Tout(a,b)\mu out + Tin(a,b)\mu in)d(a,b) \tag{5.1}$$

$$G \overset{\text{def}}{=} \{(S_1,S_1),(S_1,S_2),(S_2,S_2),(S_1,W_2\cup W_3\cup D),(S_2,W_2\cup W_3\cup D)\}$$

μin, μout - value of time in- and out-of transit vehicles ($/hr·pax).
$Tin(a,b)$, $Tout(a,b)$ - Average IVTT and OVTT for the transit demand between a and b.
$d(a,b)$ - The sum of demands between a and b [1].

The formula derivations for demand and travel times are described as below.

1) Transit Demand

Since we assume the transit demand is uniformly distributed among the entire region with the constant demand density p, the transit demand between region a and b are defined as (5.2).

$$d(a,b) = \begin{cases} \frac{2ab}{S_T}p & \text{if } a \text{ and } b \text{ are different regions} \\ \frac{a^2}{S_T}p & \text{otherwise} \end{cases} \tag{5.2}$$

Where,

$$(a,b) \in \{(S_1,S_1),(S_1,S_2),(S_2,S_2),(S_1,W_2\cup W_3\cup D),(S_2,W_2\cup W_3\cup D)\}$$

$d(a,b)$ - The sum of demands between a and b

S_T - the total area of downtown and outside of downtown

2) Out of Vehicle Travel Time (OVTT)

The out-of-vehicle travel time *Tout* consists of the average walking time to access and egress transit stops, the average waiting time, and the average transfer time. The formulas of the out-of-vehicle travel time are based on Griswold et al. (2013). Note that when $(a,b) \in \{(S_1, W_2\cup W_3\cup D), (S_2, W_2\cup W_3\cup D)\}$, only half of the walking time and waiting time occurs in downtown area, so the terms are additionally divided by 2 in (5.3).

[1] For example, $d(S_1,S_1)$ refers to the demand of which the origin and destination are both located in S_1 region. $d(S_1, W_2\cup W_3\cup D)$ refers to the influx and outflux demand between S_1 and outside of downtown.

$$
T_{aut}(a,b) = \begin{cases} (0.5r_L + 0.5r_w + s)\dfrac{1}{2V_a} + H + T & \text{if } (a,b) \in \{(S_1,S_1),(S_1,S_2),(S_2,S_2)\} \\ (0.5r_L + 0.5r_w + s)\dfrac{1}{4V_a} + \dfrac{H}{2} + T & \text{if } (a,b) \in \{(S_1, W_2 \cup W_3 \cup D), (S_2, W_2 \cup W_3 \cup D)\} \end{cases} \tag{5.3}
$$

V_a - Speed of walking (km/h)

r_L, r_w - Route spacing for bus lines (km)

s - Stop spacing for transit stops (km)

H - Headway of transit (s)

T -Average transfer time of transit (s)

3) In Vehicle Travel Time (IVTT)

The in-vehicle travel time T_{in} consists of the average cruising time and dwelling time.

$$
T_{in}(a, b) = E(a, b)\,(; + D \tag{5.4}
$$

$E(a, b)$ - Average in-vehicle travel distance in category (a, b).

v - Cruising speed of transit (km/h)

r -Average dwelling time at each transit stop (s)

Since the demand is assumed to be uniformly distributed, the average in-vehicle travel distance $E(a, b)$ is calculated as the expected distance between two random dots located in a and b with uniform probability distributions. Figure 5.2 shows an example of $E(S_1, W_3)$. The two random dots are located in the region S_1 and on the edge W_3 respectively, both with uniform probability distributions. Note that the distance between the two dots is the Manhattan distance due to the grid structure of the network.

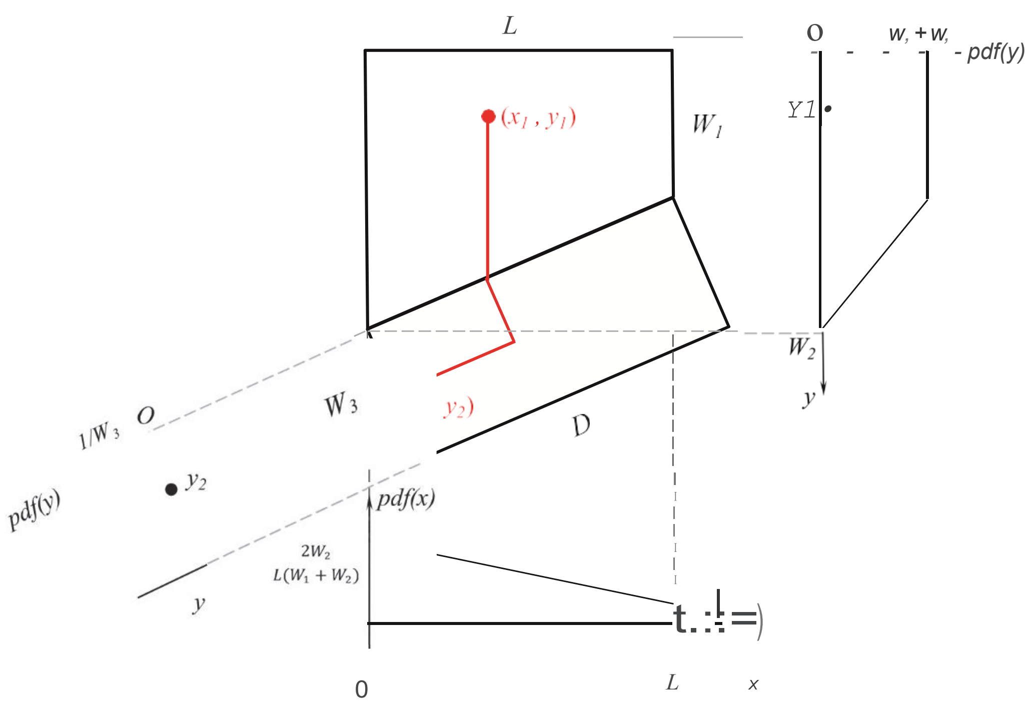


Figure 5.2 The Manhattan distance between two random dots in region S1 and on edge W3

The formulas of the average in-vehicle travel distance $E(a,b)$ for different categories are summarized in Table 5.2.

Category (a,b)	$E(a,b)$
(S_1,S_1)	$\frac{1}{6}\left(2L + 3W_1 + 2W_2 + \frac{W_1W_2(2L - 7W_1 - 3W_2)}{(W_1+W_2)^2}\right)$
(S_1,S_2)	$\frac{1}{6}\left(L + D + 3W_3 + \frac{3W_1^2 + W_2^2 + 2W_1W_2}{W_1+W_2}\right)$
(S_2,S_2)	$\frac{W_3 + D}{3}$
(S_1,W_2)	$\frac{1}{6}\left(2L + 2W_2 + \frac{W_1^3 - W_1^2W_2 + 2W_1W_2L}{W_2(W_1+W_2)}\right)$
(S_1,W_3)	$\frac{1}{6}\left(2D + 2W_1 + 3W_3 + \frac{2DW_1 + 2W_2^2}{W_1+W_2}\right)$
(S_1,D)	$\frac{1}{6}\left(L + D + \frac{3W_1^2 + W_2^2 + 2W_1W_2}{W_1+W_2}\right)$
(S_2,W_2)	$\frac{1}{6}\left(2L + D + W_1 + W_2 + 3W_3 + \frac{W_1(L + W_1 - D)}{W_2}\right)$
(S_2,W_3)	$\frac{D}{2} + \frac{W_3}{3}$
(S_2,D)	$\frac{D}{3} + \frac{W_3}{2}$
$(S_1, W_2 \cup W_3 \cup D)$	$\frac{W_2}{W_2+W_3+D}E(S_1,W_2) + \frac{W_3}{W_2+W_3+D}E(S_1,W_3) + \frac{D}{W_2+W_3+D}E(S_1,D)$
$(S_2, W_2 \cup W_3 \cup D)$	$\frac{W_2}{W_2+W_3+D}E(S_2,W_2) + \frac{W_3}{W_2+W_3+D}E(S_2,W_3) + \frac{D}{W_2+W_3+D}E(S_2,D)$

Table 5.2 Expected Manhattan distances for different demand categories

The formulas for demand and travel times are summarized in Table 5.3.

Table 5.3 Transit demand (d), out-of-vehicle travel time (OVTT) and in-vehicle travel time (IVTT) for different O-D scenarios

Category (a,b)	Demand $d(a,b)$	OVTT $Tout(a,b)$	IVTT $Tin(a,b)$
(S_1,S_1)	sf -p Sr.	(O.SrL + O.Srw + s 1)-+ H + T 2va	E(Si,51) (+D
(S_1,S_2)	25152 --p Sr,	(O.SrL + O.Srw + s)1 -+ H + T 2va	E(Si,52) (+)
(S_2,S_2)	sJ -p Sr.	(O.SrL + O.Srw + s) 1 + H + T 2 Va	D E(S2,S2) (+
$(S_1,W_2\cup W_3\cup D)$	$\frac{2S_1(S_\Sigma-S_1-S_2)}{S_\Sigma}\rho$	(0.SrL + O.Srw + s)-1 + H - + T 4va 2	E(Si,W2 ∪ W 3 ∪ D) (+)
$(S_2,W_2\cup W_3\cup D)$	$\frac{2S_2(S_\Sigma-S_1-S_2)}{S_\Sigma}\rho$	(O.SrL + 0.Srw + s 1)-+ H - + T 4va 2	$E(S_2,W_2\cup W_3\cup D)\left(\frac{1}{v}+\frac{\tau}{s}\right)$

i) Category (a,b) refers to the group of the transit demand where the origin and the destination are located respectively in *a* and *b*, *orb* and *a*.
ii) Sr, is the total area of downtown and outside of downtown.
iii) $E(a, b)$ refers to the average in-vehicle travel distance in category (a, b).

5.1.2 Agency cost and transit emissions

The agency cost *Cagency* consists of the costs to construct and maintain transit infrastructure and stations, the costs to operate and maintain transit vehicles, and the cost of labor (Griswold et al 2013). For MUNI transit buses, the routes and stops costs are small compared to the vehicle and labor costs, and therefore only the latter two are considered in this paper for simplification (5.5).

C agency- - (W1 + Wz)L + 2W3D(1 1) sH Pw + - PL v

+ ((W1 + W 2) L + 2W3D 1 - + 1 -) (1 - + r -) CM

sH Pw PL v s

CM - Labor

Cv - Vehicle purchase, fuel & maintenance cost ($/veh·km) cost (\$/veh·hr)

P_W, P_L - Route spacing factor. They are equal to $\frac{r_W}{s}, \frac{r_L}{s}$ respectively. (5.5)

Transit emissions *Etransit* include the emissions resulting from constructing and maintaining transit infrastructure and stations, and the emissions from operating and maintaining transit vehicles (Griswold et al 2013). For MUNI transit buses, the latter are much higher and are considered exclusively in this paper (5.6).

$$E_{transit} = \frac{(W_1 + W_2)L + 2W_3 D}{sH}\left(\frac{\ }{P_w} + \frac{2}{P_L}\right)E_v \tag{5.6}$$

E_v - Vehicle fleet manufacturing, operation & maintenance emissions (g/veh·km)

5.2 Evaluation of the stylized network

We evaluate the costs and emissions of the stylized network by assigning values to the attributes in the formulas (5.1) through (5.6). The values assigned reflect the current state of the actual transit network and are calculated based on real transit traffic data and agency annual report (Table 5.4).

Table 5.4 Values of system attributes reflecting current state

Attribute	Value
density (pax/km^2·hr)	234
average headway (min)	12.54
average stop spacing (m)	120
average route spacing (m)	360

The cost- and emission-comparisons between the continuum approximation (CA) on the stylized network and the actual data on the real network are shown in Table 5.5.

Table 5.5 Comparison of results obtained by the CA method and real data

	Real Network	Approximation using CA	Relative Error
Total Cost (billion $/yr)	0.304	0.300	1.3%
Transit Emissions (1000 mt GHG/yr)	5.209	4.635	11%

It can be seen from Table 5.5 that the total costs and transit emissions obtained are quite close to the actual values with around 10% relative error. Although we have neglected the complex real network details, the low relative error suggests that the proposed stylized network is a good representation of the real network regarding the cost and emission measurements. Furthermore, the closed-form expressions of the costs and emissions allow for efficient computations in the optimization described in Chapter 6.

Chapter 6 Implementation: Transit Network Optimization

In Chapter 5, we used the stylized network and the continuum approximation method to represent the real network. The decision variables (H, *s, rw, rL)* were assigned fixed values reflecting the current state of the real network. In this chapter, we solve for the optimal values of these decision variables using the model formulation defined in (3.1). Particularly, the goal is to solve for the values of the decision variables that minimize the total costs subject to a MUNI bus emissions constraint.

Similar to Chapter 3 and 4, a Pareto curve for optimal bus system design for MUNI is obtained (Figure 6.1), allowing for comparison between the system's optimal and current state of operations. Furthermore, the comparison of the decision variable values provides insights regarding design and operational modifications for the purposes of cost and emission minimization (Table 6.1).

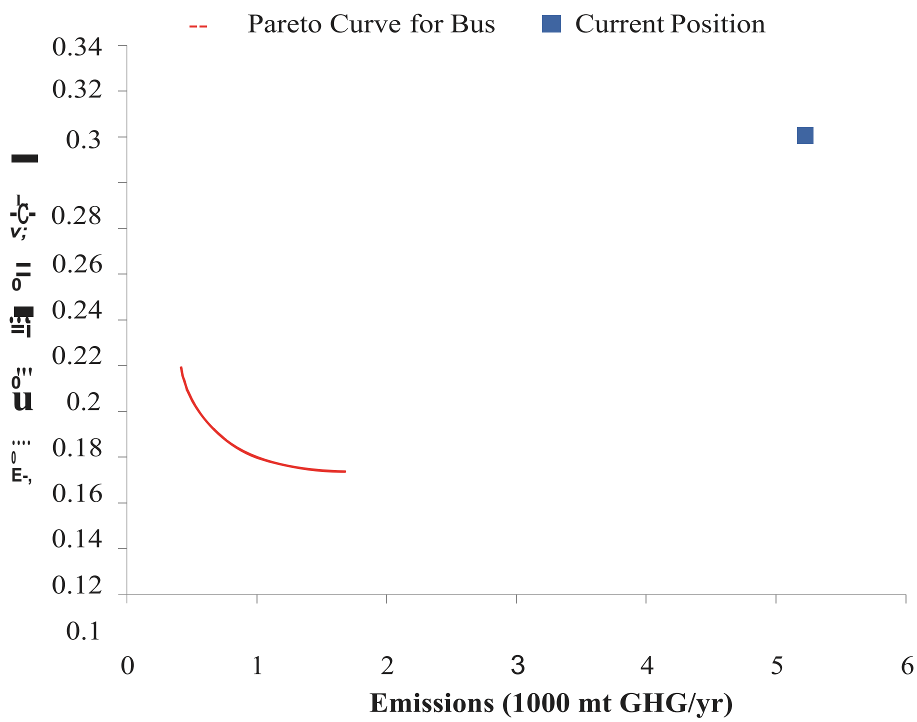


Figure 6.1 The current state of the MUNI network and the Pareto frontier

Figure 6.1 shows the current state of the network and the Pareto frontier obtained by the network optimization. As conjectured earlier, the current MUNI bus system does not lie on the Pareto frontier. The relative position of the point of the current state with respect to the Pareto frontier demonstrates the potentials for cost and emission reduction via transit network optimization. The current state of the system has higher societal costs and GHG emissions compared with those of the cost-optimal state. In this context, transit agencies may achieve simultaneously the reductions in societal costs and GHG emissions simply by bringing the system from its current state to the cost-optimal state. The tradeoffs between the costs and emissions, as described in the previous chapters, only exists if one wants to achieve further emission reductions starting from the cost-optimal state.

Table 6.1 Attributes for the network on the Pareto Frontier

Route Spacing (N-S route) (km)	Route Spacing (W-E route) (km)	Stop Spacing (km)	Headway (min)	Ctotal (B$/yr)	Cuser (B$/yr)	Cagency (B$/yr)	Emissions (mt/yr)	TT (min)	IVTT (min)
1.03	1.03	0.51	6.08	0.15	0.121	0.032	1680	15.3	7.0
1.10	1.10	0.55	7.16	0.16	0.130	0.025	1330	16.0	6.9
1.36	1.36	0.45	7.85	0.16	0.141	0.020	980	17.3	7.3
1.45	1.45	0.48	8.87	0.17	0.149	0.016	820	18.0	7.1
1.52	1.52	0.51	9.65	0.17	0.156	0.014	710	18.6	7.0
1.70	1.70	0.43	9.89	0.18	0.163	0.013	620	19.5	7.4
1.76	1.76	0.44	10.49	0.18	0.168	0.011	570	19.9	7.3
1.74	2.17	0.43	11.65	0.19	0.180	0.009	460	21.2	7.4
1.74	2.17	0.43	11.65	0.19	0.180	0.009	460	21.2	7.4
1.66	2.50	0.42	12.19	0.20	0.187	0.009	430	21.9	7.5

Table 6.2 Comparisons between the current state and the cost-optimal state

Attributes	Current State	Cost-optimal State
Route Spacing (N-S route) (km)	0.36	1.03
Route Spacing (W-E route) (km)	0.12	1.03
Stop Spacing (km)	0.12	0.51
Headway (min)	12.5	6.1
Ciotal (billion $/yr)	0.30	0.15
Cuser (billion $/yr)	0.152	0.121
Cagency (billion $/yr)	0.148	0.032
Emissions (mt/yr)	4640	1680

We compare the current state with the cost-optimal point on the Pareto frontier (Table 6.2). It is observed that significant reductions in total cost and emission may be achieved simultaneously by increasing route and stop spacing and decreasing headway. Therefore, a bus service plan with lower spatial availability but higher temporal availability may be more favorable. This suggests that there may be benefits to decreasing local bus service and providing more frequent express bus service. For a small city like San Francisco, the average walking distance is small. Local bus service (with small stop spacing) may cause unnecessary user cost by stopping too often. By increasing walking distance, which increases walking time, an express bus service (with large stop spacing) saves users' IVTT significantly by stopping less frequently. Furthermore, the reduced headway saves users' average waiting time at transit stops. As a result, we can observe that the cost-optimal state has lower user cost than the current state, as shown in Table 6.2. The overall transit LOS was not reduced. In fact, the cost-optimal state was found to have a higher transit LOS than the current state, as can be seen in the comparisons of the user costs in Table 6.2. In this case, transit agencies may not need to worry about the unintended consequences due to the potential demand shift.

Chapter 7 Conclusions and Recommendations

Quantifying the potential tradeoffs between level of service and emissions can help transit agencies select the trunk transit technology and optimal network attributes for hierarchical transit grid systems. In this research, we have developed an analytical model for hierarchical transit systems, and researched the economic and environmental competitiveness of different transit technologies in various city scenarios. The demand elasticity between transit and automobile, the demand split between transit and walking, and the demand split within the transit system have also been incorporated in the model. Compared to previous studies (Griswold et al. 2013, Chester and Horvath 2009, Chester et al. 2010, Sivakumaran et al. 2014), this study incorporated demand elasticity and the transit hierarchy simultaneously when assessing costs and emissions, providing a more complete picture that can better assist transit agencies in designing and operating transit systems.

7.1 Results

The analysis in this research shows that, in small cities, trunk-only bus systems are more cost- and emission-competitive than hierarchical transit systems. On the other hand, in large cities, both societal costs and emissions reductions can be achieved by deploying hierarchical transit systems with mass transit modes such as metro as the trunk technology. These results are different from earlier findings in the literature (Griswold et al. 2013), which were based on analyses of trunk-only transit systems.

The results show that incorporating a feeder system not only increases the relative competitiveness of capital-intensive transit technology with respect to total costs, which had been already demonstrated in Sivakumaran et al (2014), but also emissions. The analysis also shows that, for cities that have metro as the trunk mode, it is not necessary to design or operate the system near the cost-optimal point as significant emission reductions are possible, without incurring large additional societal cost relative to the optimal cost. The sensitivity analysis shows that these findings regarding modes comparisons are robust to variations in the costs and emissions parameters.

Transit demand elasticity offsets transit emissions reduction efforts by causing additional automobile emissions due to demand shifting away from transit. For metro, there exists a phase of decreasing total emissions as the LOS is lowered even for highly elastic transit demand. However, when transit demand is highly elastic for bus, BRT or LRT, reducing LOS will cause a net increase in city-wide emissions. These findings suggest that some cities may benefit from lowering transit LOS while others may not, depending on their trunk transit technology and transit demand elasticity. The size of the city also matters when making such decisions: for a large city, it is not recommended to reduce the LOS of metro if the demand is highly elastic.

Imposing an emissions budget on the entire city instead of the individual agencies is a safer course of action to avoid unintended emission backfire and achieve emissions reductions. However, transit demand elasticity is a key factor in determining the magnitude of such reduction potentials. In light of this, agencies should make a thorough investigation of transit demand composition (i.e., the fractions of captive and non-captive users) and flexibility before any LOS-emissions policy is passed.

In reality, it is possible for many transit systems to reduce GHG emissions without sacrificing transit LOS because many of them are not yet efficiently designed to operate at the cost-optimal point. In this situation, Pareto-improving solutions are possible. The work presented in Chapter 5 and 6 demonstrated such a transit system, the MUNI bus network for the city of San Francisco. By optimizing the system's design and operation to minimize societal costs, GHG emissions are significantly reduced. The cost-optimal MUNI bus system has a societal cost of 0.15 billion $/year and emits 1680 metric tons of greenhouse gases. These figures only amount to about half of the cost and a third of the emissions in the current MUNI bus system.

This may be an encouraging message for many current transit agencies that are improving transit systems to achieve minimum costs. General concerns regarding transportation cost minimizations often includes potential negative environmental impacts. The findings in this study suggest that this is not necessarily true for current transit systems. Urban transit systems that minimize societal costs may also reduce GHG emissions.

Our analysis shows that the cost-optimal state of the MUNI bus system has lower spatially availability but higher temporal availability than the current system. This suggests the potential benefits of decreasing local bus service and providing more frequent express bus service. The overall transit LOS was not reduced. In fact, the cost-optimal state was found to have a higher transit LOS than the current state.

7.2 Limitations and Future Work

It is worthwhile to note that there are limitations in this research that might have hindered more insights in the problem. The transit demand in this study has been assumed to be distributed uniformly throughout the entire city. This might be close to reality when cities are small or we are solely analyzing small regions such as downtown areas. Yet for larger cities, a non-uniform demand distribution should be more realistic. Future work may address this issue by introducing various layers or spikes of transit demand to simulate downtown areas and large trans-mode stations.

Four different trunk transit technologies are considered in this study. They are all assumed to be accessed by walking and feeder buses. In the real world, there are usually many more combinations of transit modes for completing daily travels. As a result, another extension of this study would be to include more potential transit mode combinations in the hierarchical transit system design. For example, many cities have both metro and buses as trunk transit in highly demanded regions. Transit users may have their own preferences when deciding which transit to take. Furthermore, the transit system design need not be "transit-exclusive" since transit users may consider non-transit modes for parts of their trips, such as the situation where people drive to the nearest metro stations. A more macroscopic transit design scheme with more balanced views of urban transportation compositions should benefit the society in the long term.

The latter part of the research has utilized a stylized grid transit network for the case study. Even though the network has been evaluated to be a good representation of the real network regarding the cost and emission estimations, there are other concerns that might be of importance in future works. For example, cities that have ring and radial transit networks, such as Chicago and Paris, may require a different set of stylization procedures before applying the continuum approximation method. In this context, the Cartesian coordinate system needs to be replaced by the polar coordinate system. In the situations where cities have even more complex network structures, the stylization procedures should be done on a case by case basis.

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Appendix A Expected travel distance in a rectangular city

We assume that the demand is evenly distributed in a rectangular city with length Land width W. The origins and destinations for transit users can be represented by coordinate pairs (x_0, y_0), (x_0, y_0). x_0 and x_0 are assumed to be uniformly distributed between O and L, Yo and Yo are assumed to be uniformly distributed between O and W. The trip distance $Z = |x_D - x_0| + |Y_V - Yo|$ has the following probability density function $fz(z)$ (Fairthome 1965):

$$fz(Z) = \begin{cases} \frac{2z}{3L^2W^2}(6LW - 3z(L + W) + z^2) & \text{for } 0 \quad z \quad W \\ \frac{2}{3L^2}(3L + W - 3z) & \text{for } W \quad z \quad L \\ \frac{2}{3L^2W^2}(L + W - z)^3 & \text{for } L \quad z \quad W + L \end{cases}$$

Sivakumaran et al. (2014) have derived the formulas for calculating the expected travel distance considering the critical distance, de, which splits the demand between the trunk transit and the feeder transit. This study extends their considerations by incorporating another critical distance, d_0, under which the users will choose to walk. The conditional expectations in (3.16) are defined as below:

$$d_w = \mathrm{E}(Z|Z \leq d_0) = \frac{\int_0^{d_0} t f_Z(t)\, dt}{\int_0^{d_0} f_Z(t)\, dt}$$

$$d_f = \mathrm{E}(Z|d_0 < Z \leq d_c) = \frac{\int_{d_0}^{d_c} t f_Z(t)\, dt}{\int_{d_0}^{d_c} f_Z(t)\, dt}$$

$$d_t = \mathrm{E}(Z|Z > d_c) = \frac{\int_{d_c}^{L+W} t f_Z(t)\, dt}{\int_{d_c}^{L+W} f_Z(t)\, dt}$$

It is reasonable to assume that d_0 W. By evaluating the integrals above, we get the following expressions:

$$d_w = \frac{d_0(40LW - 15Ld_0 - 15Wd_0 + 4d5)}{5(12LW - 4Ld_0 - 4Wd_0 + d5)}$$

$$\begin{cases} \frac{40LW(d + dadc + dn - 1S(L + W)(d + d\,dc + dad + dn + 4(d6 + d\,dc + d\,d + dad + dn}{5(12LW(da + dJ - 4(L + W)(d6 + dadc + dn + d6 + d6\,dc + d\,ad + d)} & \text{for } 0 :5 z :5 W \\ \frac{SLW(W^3 - 6Wd + 8dg) - 1S(L + W)d6 + W^5 - 10W^3d + 20W^2d + 4dg}{5(4LW(W^2 - 3Wd + 3d6\} - 4(L + W)dg + W^4 - 4W^3d + 6W^2d + dci)} & \text{for } W :5 z :5 L \\ \frac{SLW(L^3 + W^3 - 6(L + W)d + S(dg + d)) + L^5 + W^5 - 10d(L^3 + W^3 + 2dJL' + w')) - 1s(d6 + d;)(L + w) + 4(d + d!)}{5(4LW(L^2 + W^2 - 3(L + W)d, + 3d + 3d;) + L^4 + W^4 - 4(L^3 + W^3)d, + 6(L^2 + W^2)d; - 4(L + w)(d + dn + d6 + di)} & \text{for } L :5 z :5 W + L \end{cases}$$

$$\frac{2L^3W^2 + 2L^2W^3 - 8LWdJ + 3(L + W)dt - 4/Sd}{6L2W^2 - l2LW d + 4(L + W)dJ - dJ} \qquad for\ O \quad z \quad W$$

$$\frac{10L^3 + l0L^2W + 5LW^2 - 30Ld + W^3 - l0Wd + 20dJ}{15W^2 + 20W de - 60LW - 30d + 60Ldc} \qquad for\ W \quad z \quad L$$

$$\frac{1}{5}(L + W + 4d_c) \qquad for\ L \quad z \quad W + L$$

Appendix B Attributes, cost and emission parameters used in the MUNI system analysis

The values for the network attributes, cost and emission parameters of the MUNI bus system are shown in Table B.1.

Table B.1 Network attributes, costs and emissions parameters of the MUNI bus system

Param	Description	Units	Value	Note
L	Bay Street	km	2.52	
D	Harrison Street	km	3.13	
$W1$	The Embarcadero	km	1.41	
$W2$	Van Ness Avenue	km	3.27	
$W3$	11th Street	km	0.78	
p	Demand density	pax/km^2-hr	234	See subsection 1)
v_a	Speed of walking	km/h	5	Griswold et al. (2013)
V	Cruising speed	km/h	13	Griswold et al. (2013)
τ	Lost time/stop	sec.	30	Griswold et al. (2013)
T	Lost time/transfer	sec.	20	Griswold et al. (2013)
C_v	Vehicle purchase, fuel & maintenance cost	\$/veh-km	4.88	See subsection 2)
C_M	Labor cost	\$/veh-h	187	See subsection 2)
E_v	Vehicle fleet manufacturing, operation & maintenance emissions	g/veh-km	796	See subsection 3)

1) Demand density *(p)*

The average daily ridership for MUNI is approximately 679800 pax. The entire area of San Francisco (SE) is 121 km^2. As a result, the demand density can be calculated as below.

$$p = \frac{67800 \text{ pax/day}}{24 \text{ hr/day} \times 121 \text{ km}^2} = 234 \text{ pax/km}^2 \cdot \text{hr}$$

2) Vehicle purchase, fuel and maintenance cost (C_v), Labor cost (CM)

The cost parameters C_v and C_M are calculated based on the data from SFMTA (2013). Table B.2 shows the annual expenses for the MUNI bus system in fiscal year 2012-2013.

Table B.2 Expenses for the MUNI bus system in fiscal year 2012-2013 (SFMTA 2013)

Operating Expenses	(\$ in thousands)
Personnel services	529,607
Contractual services	48,783
Materials and supplies	78,346
Depreciation and amortization	118,350

Total operating expenses	775,086

In this study, the sum of personal services and contractual services is considered as labor costs, materials and supplies refer to fuel and maintenance cost, depreciation and amortization are related to vehicle purchase cost. As a result, the vehicle purchase, fuel and maintenance cost per year for MUNI system is \$118,350,000 + \$78,346,000 = \$196,696,000/year.
The total passenger miles of MUNI system in the year 2011 is approximately 451,070,000 pax-miles (APTA 2013). The average occupancy on bus is 18 pax/veh (APTA 2013). The vehicle-miles-traveled (VMT) per year for MUNI can thus be calculated.

$$VMT = \frac{451070000 \text{ pax} \cdot \text{mile}}{18 \text{ pax/veh}} = 25059444 \text{ veh} \cdot \text{mile}$$

The parameter *Cv* can be obtained as below.

$$Cv = \frac{\$196696000}{25059444 \text{ veh} \cdot \text{mile} \times 1.609 \text{km/mile}} = \$4.88/\text{veh} \cdot \text{km}$$

The labor cost for MUNI system is \$529,607,000 + \$48,783,000 = \$578,390,000/year. The total vehicle-hour-traveled (VHT) per year for MUNI can be calculated by dividing the VMT by the cruising speed *v*.

$$VHT = \frac{25059444 \text{ veh} \cdot \text{mile}}{8.1 \text{ mile/hr}} = 3093759 \text{ veh} \cdot \text{hr}$$

The parameter *CM* can be obtained as below.

$$CM = \frac{\$578390000}{3093759 \text{ veh} \cdot \text{hr}} = \$187/\text{veh} \cdot \text{hr}$$

3) Vehicle fleet manufacturing, operation and maintenance emissions *(Ev)*
The current fleet of the Muni system is summarized in Table B.3.

Table B.3 Fleet of the Muni system (SFMTA 2007)

Bus type	Quantity
Diesel buses	253
Diesel-electric hybrid buses	258
Trolley buses	333
Light-rail vehicles	149
Historic streetcars	50
Cable cars	40

San Francisco's trolley coaches (as well as its streetcars and the cable motors for the cable cars) are almost entirely pollution-free, since their electric power comes from the city's hydroelectric Retch Hetchy Water and Power Project (SFMTA 2015). Therefore, the operating emission rate for trolley buses, streetcars and cable cars should be treated as zero in this study since the electricity is 100% hydroelectric. Based on Hallmark et al. (2013), we assume the vehicle manufacturing emission rate (258 g/veh-mi) and maintenance emission rate (45 g/veh-mi) are the same among all buses and the operating emission rate of the hybrid buses is about 37% lower than that of diesel buses in MUNI. The emission rates of different types of buses are summarized in Table B.4.

Table B.4 Emission rates of different types of buses

	Manufacturing emission rate (g/veh-mile)	Maintenance emission rate (g/veh-mile)	Operating emission rate (g/veh-mile)	Total emission rate (g/veh-mile)	Quantity
Diesel buses	258	45	2400	2703	253
Hybrid buses	258	45	1752	2055	258
Other buses	258	45	0	303	572

As a result, the average fleet emission rate is:

$$Ev = \frac{\mathbf{253 \times 2703 + 258 \times 2055 + 572 \times 303}}{253 + 258 + 572} \qquad 1281\,\mathrm{g/veh \cdot mile}\ 796\,\mathrm{g/veh \cdot km}$$