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Planning Hierarchical Urban Transit Systems for Reductions in Greenhouse Gas Emissions

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Abstract

Public transit systems with high occupancy can save greenhouse gas (GHG) emissions. However, current transit systems had not been designed to reduce environmental impacts. This motivates the study of the benefits of optimal design and operational approaches to reducing the environmental impacts of transit systems. Transit agencies could resort to level-of-service (LOS) changes, for example, reductions in vehicle kilometers traveled. In previous work, we explored the unintended consequences of lowering transit LOS on emissions from a single-technology transit systems. Herein we extend the analysis to account for a more realistic case: a transit system with hierarchical structure (trunk and the feeder lines) providing service subject to demand elasticity. By considering the interactions between the trunk and the feeder systems, we provide a quantitative basis for designing and operating integrated urban transit systems that can reduce GHG emissions and societal costs. We find that large cities may achieve societal cost as well as emission savings by employing a hierarchical structure, while the non-hierarchical structure may be better for small cities. Highly elastic transit demand may cancel emission reduction potentials, yet for mass transit modes these potentials are still significant. Transit networks with buses, bus rapid transit or light rail as trunk transit modes should be designed and operated near the cost-optimal point when the demand is highly elastic, while this is not required for metro.

Key words: transit system design; greenhouse gas emission; feeder transit; elasticity

1. Introduction

In recent years, public transportation's role in reducing greenhouse gas (GHG) emissions has started to receive increased attention. Compared to automobiles, public transit systems with high occupancy rates can reduce GHG emissions significantly (Hodges 2010). However, most 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).

One potential approach to reducing transit GHG emissions is through lowering the operational frequency and spatial coverage, i.e., the level of service (LOS) (Shrestha and Zolnik 2013, Saka 2003). Though unconventional and undesirable to captive transit users, 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.

In earlier work (Griswold et al., 2014), we explored the unintended consequences of such emission reduction efforts. We considered a hypothetical city with a grid trunk transit network, and compared four trunk line modes – bus, bus rapid transit (BRT), light rail transit (LRT), and metro – with walking as the access mode. In the cases of bus, BRT and LRT, we found that lowering the transit LOS may increase the city-wide emissions as some transit users switch to faster but more polluting automobiles. This could result in lose-lose-lose outcomes for city agencies, transit users, and the environment. We also found that the case of metro was not comparable with other cases: it produced a significantly higher level of emissions at any level of service. Metro is neither cost-competitive (Sivakumaran et al. 2014) nor emission-competitive when access is restricted to walking.

In reality, urban transit networks 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 use feeder modes to access trunk transit.

In this letter, we improve upon the approach shown in Griswold et al. (2014) by quantifying the LOS-emissions relationship for a transit system with hierarchical network structure. This provides more realistic insights, especially for cities that have metro as the trunk transit technology. The dimensionality of the problem also increases due to the interactions between trunk transit and feeder transit. We assume transit passengers may use either a single or a sequence of transit modes to complete their travels based on the locations of their origins and destinations.

Continuum approximation (CA) methods are employed to estimate the costs and emissions of the transit system. Decision variables include headways, stop spacings, and route spacings of the trunk and feeder transit. The entire hierarchical transit network is optimized for minimizing GHG emissions and total societal costs. This bi-objective optimization is transformed into a constrained optimization problem where we minimize the societal costs subject to a GHG emissions constraint, as described in section 2. The Pareto frontier of costs and emissions is obtained by varying the emissions constraint, allowing for evaluating the cost- and emission-effectiveness of the hierarchical transit system, as described in section 3. Because emissions reductions are achieved through lowering the transit LOS, we discuss the effect of potential mode shift on the total emissions in section 4.

2. Formulation

We consider a simplified hierarchical grid transit network 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 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 feeder 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 feeder 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 feeder 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. We call the zone “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 (ρ). 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 1.

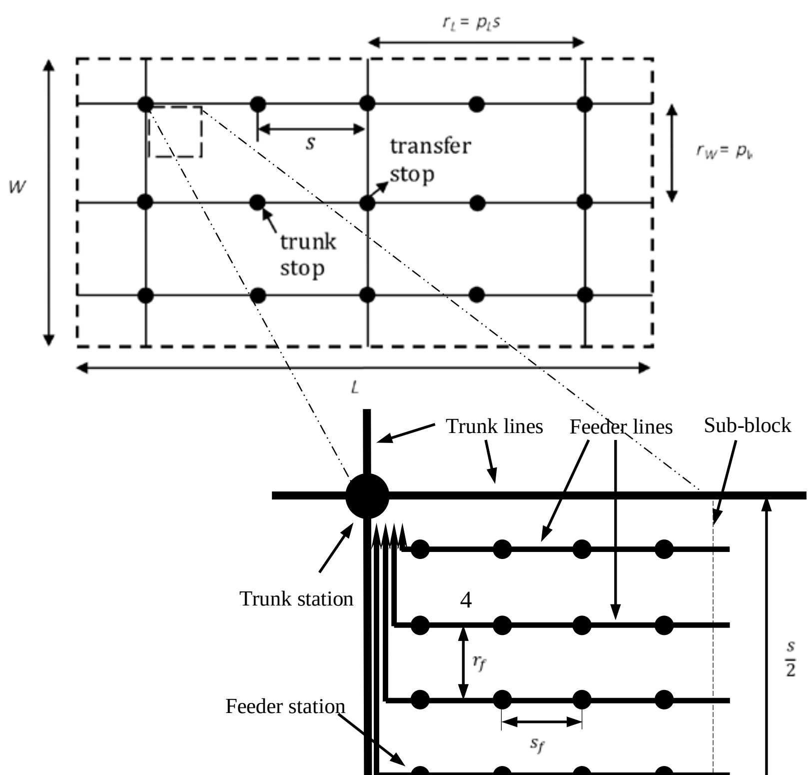


Figure 1 Hierarchical transit network for this study

Where:

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

r_W, r_L – Route spacing for trunk lines.

s – Stop spacing for trunk transit stops.

r_f – Route spacing for feeder lines.

s_f – Stop spacing for feeder transit stops.

It should 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 the feeder system may cause unnecessary intra-modal transfer times and feeder emissions. However, for large cities, adopting a trunk-only bus system may not be feasible due to limited bus capacity. To verify these conjectures, we also consider trunk-only bus systems to compare with the hierarchical systems described above.

The formulation of the problem builds on the work of Sivakumaran et al. (2014), Griswold et al. (2013) and Griswold et al. (2014). 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 (Eq. 1). Decision variables include headways, stop spacings, and route spacings for the trunk and feeder systems: H, h, s, s_f, r_W, r_L, r_f. The cost- and emission-terms in Eq. 1 are functions of these decision variables. The goal 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. 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}.

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

$$s.t. \;\; E_{emissions,T} \leq E \qquad \text{(Eq. 1)}$$

$$Load \leq Kap$$

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 of transit system

E – Budget of greenhouse gas emissions

$Load$, Kap – Transit load and capacity

The specific derivations of the cost- and emission-terms above are provided in the Supplemental Information (SI). In brief, the cost to transit users (C_{user}) is measured by monetized average travel time, where the travel time is the sum of the access and wait time and the in-vehicle travel time for both the feeder and trunk transit. The cost to transit agencies (C_{agency}) results from construction and maintenance of transit infrastructure, vehicle purchase and maintenance, fuel purchase, and labor. The transit emissions ($E_{emissions,T}$) result from the construction and maintenance of transit infrastructure, and vehicle manufacture, operation, and maintenance.

3. Comparisons of hierarchical transit systems with different trunk line technologies

To provide insights from the generalized model described above, it is necessary to adjust the model attributes as close as possible to the attributes of real cities. We employ two scenarios (Table 1) that are similar to San Francisco and New York City, which represent, respectively, typical small and large cities with grid networks and high transit demand density.

Table 1 City scenarios

	City size (L, W) (km)	Demand density (ρ) (passengers/km^2/h)
Scenario 1 (similar to San Francisco)	10	200
Scenario 2 (similar to New York City)	40	200

Mode attributes, costs and emission factors for the trunk transit and feeder transit are provided in the SI. 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, LRT on the Muni light rail system, and metro on the Bay Area Rapid Transit (BART) system. For the feeder transit system, we consider only one mode: feeder bus (usually smaller buses or vans designed mainly for local service). 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 (as shown in the SI) to allow for more updated emissions estimates.

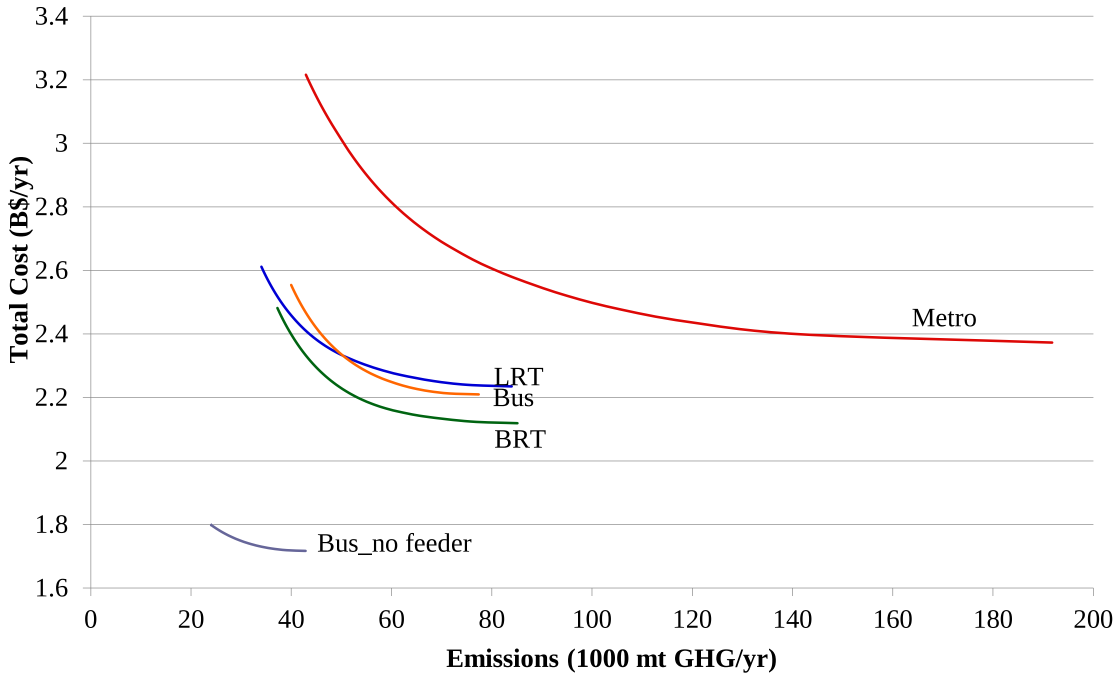


Figure 2. Technology-specific Pareto curves of system costs and transit emissions (scenario 1) (mt = metric tons)

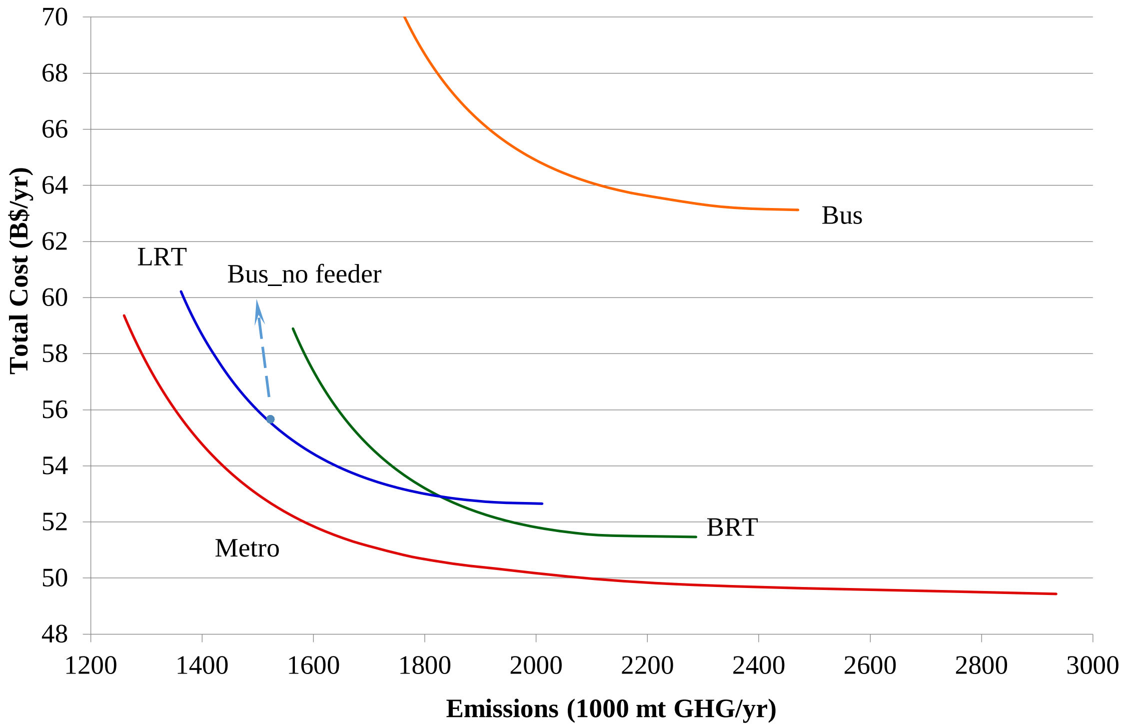


Figure 3 Technology-specific Pareto curves of system costs and transit emissions (scenario 2)

Figure 2 shows the Pareto frontiers for the optimal transit system designs for different trunk technologies for 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 because 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 feeder access. The intramodal 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, which is a common case in reality, LRT or buses are better than BRT in saving 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. In summary, incorporating feeder access does not increase the cost- and emission-competitiveness of the bus system in scenario 1 since societal costs and emissions are much higher compared with the trunk-only bus system.

For large cities (scenario 2), 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 significant costs by requiring fewer kilometers of the expensive metro infrastructure. This can be verified in Figure 3, where metro is the lowest-cost option for all 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. For example, the GHG emissions of metro can be reduced by 17% from 2,900 metric tons (mt) GHG/yr to 2,400 mt GHG/yr with only a 1% increase in societal costs (from $49.4 billion per year to $49.8 billion per year).

It should be noted that in generating the Pareto curve of the trunk-only bus system in large cities (scenario 2), 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 it is achieved through lowering the operational frequency and spatial coverage, which will result in bus overloading when 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 Figure 3. 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. Effect of mode shift on GHG emissions

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. Demand elasticity for transit travel time (b) is used to measure how sensitive the transit users are to the changes in transit LOS. To examine how the GHG emissions are affected by the changed demand due to reductions in service, curves showing the relationships between the total GHG emissions ($E_{emissions,T} + E_{emissions,auto}$) and total transit travel time are developed for different trunk technologies. $E_{emissions,auto}$ denotes the marginal automobile emissions due to users switching from transit to cars. The equation used to compute the changes in emissions as a function of elasticities and travel times can be found in the SI. We base the analysis of the elastic case on scenario 1 with the transit hierarchy. 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 trunk technologies. To account for this variability, we examine the impact of b between 0.0 and -1.0 on the emissions-travel time curves.

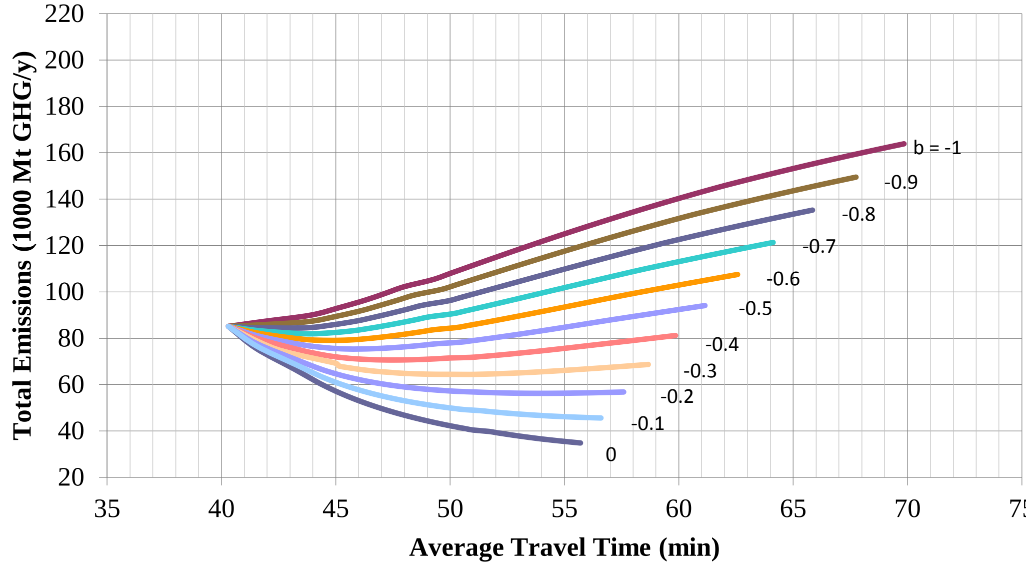


Figure 4 Change in total emissions with travel time as LOS is reduced for BRT

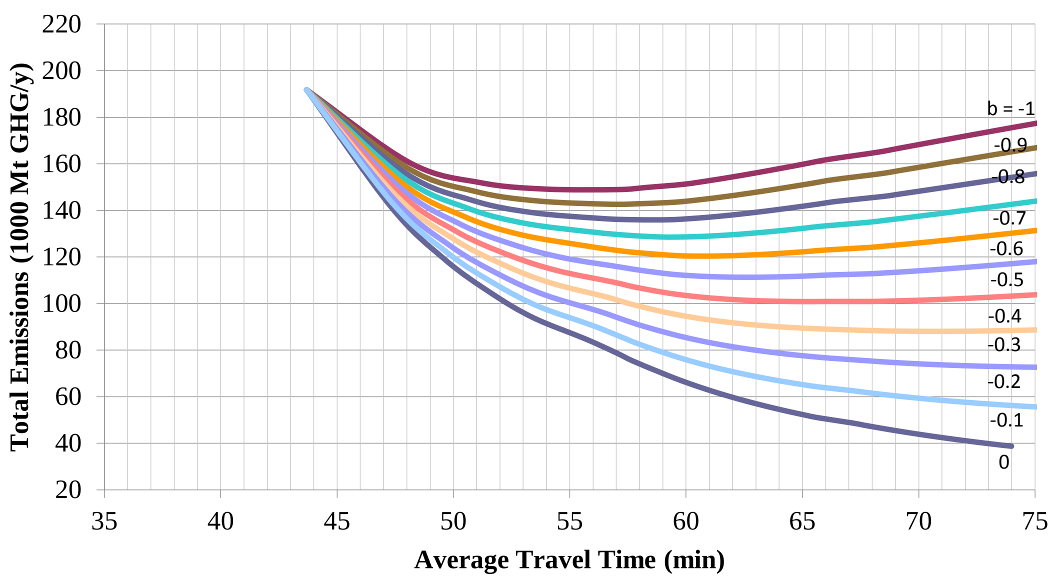


Figure 5 Change in total emissions with travel time as LOS is reduced for metro

Figures 4 and 5 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 fair 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 hierarchical BRT system (Figure 4), the elasticity values -0.9 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 detrimental to both user travel times and emissions. When the elasticity values are between -0.7 and -0.8, there is initially a small emissions benefit as the transit LOS is lowered. However, as the transit travel time approaches 45 minutes (i.e., increases by about 10%, or 5 minutes relative to the baseline travel time), the emissions start to increase. The elasticity values between 0 and -0.3 produce monotonically decreasing emissions. The elasticity values between -0.4 and -0.6 produce slight or no emissions reductions over the travel time values shown. The cases of the hierarchical bus and hierarchical LRT systems have similar relationships between total emissions and travel time as in Figure 4. As a result, 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 5), emissions reductions are possible for all the elasticity values. The reductions are especially significant as the LOS is lowered from the cost-optimal value. 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 (Eq. 1) where the emissions constraint is imposed on the transit system alone. As was shown earlier, 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 1) emissions budget, where the emissions constraint is imposed on the entire city rather than only on the transit system, as shown in Eq. 2:

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

$$s.t. \quad E_{emissions,T} + E_{emissions,auto} \leq E \qquad \text{(Eq. 2)}$$

$$Load \leq Kap$$

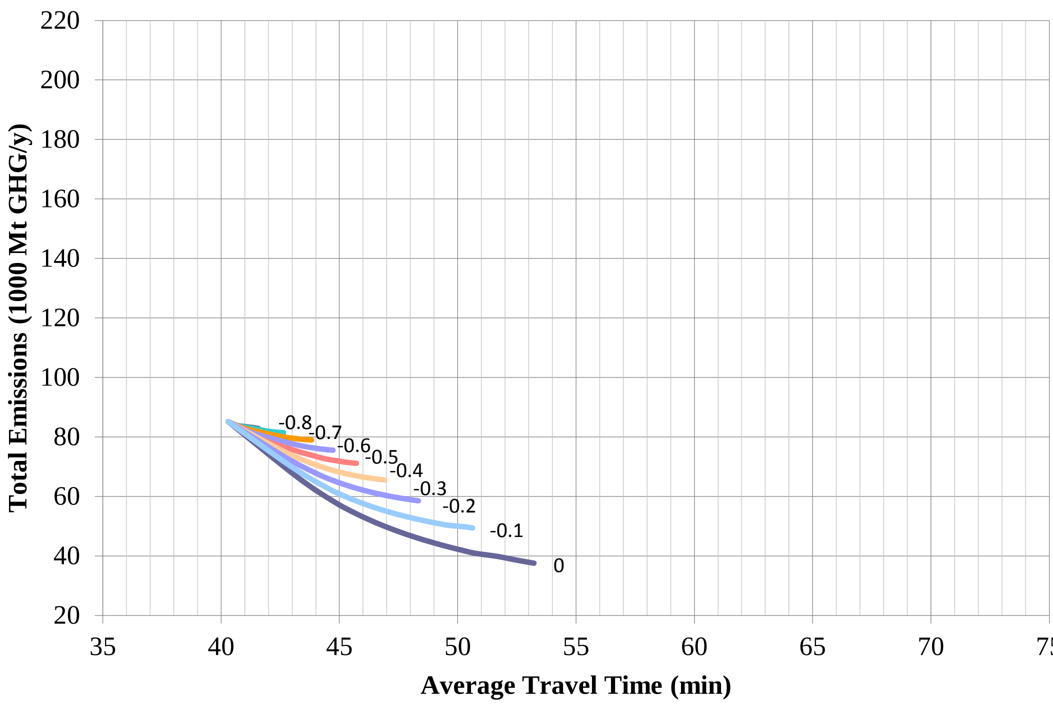


Figure 6 Change in total emissions with travel time as LOS is reduced for BRT under a city-wide (scenario 1) emissions budget

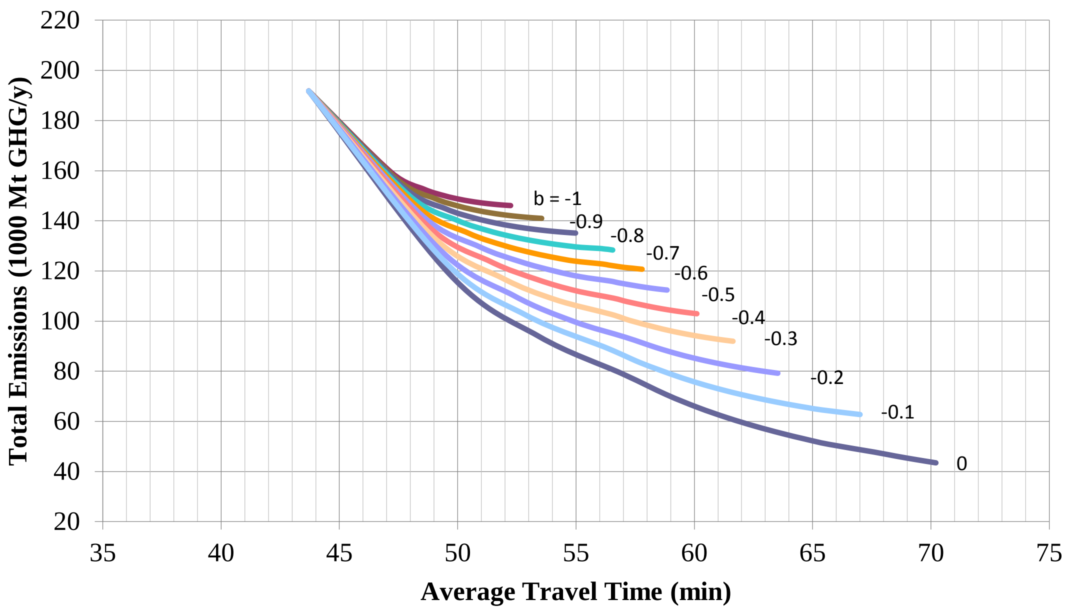


Figure 7 Change in total emissions with travel time as LOS is reduced for metro under a city-wide (scenario 1) emissions budget

Figures 6 and 7 show the results of this optimization. Increases in total emissions are avoided because they are constrained by E in Eq. 2. Compared with Figures 4 and 5, 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. 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.

5. Effect of city size on emissions

In the previous section we study the elastic case based on a small city (scenario 1), and verify that for the hierarchical metro system, there always exists a phase of decreasing total emissions as the 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 2) in this section.

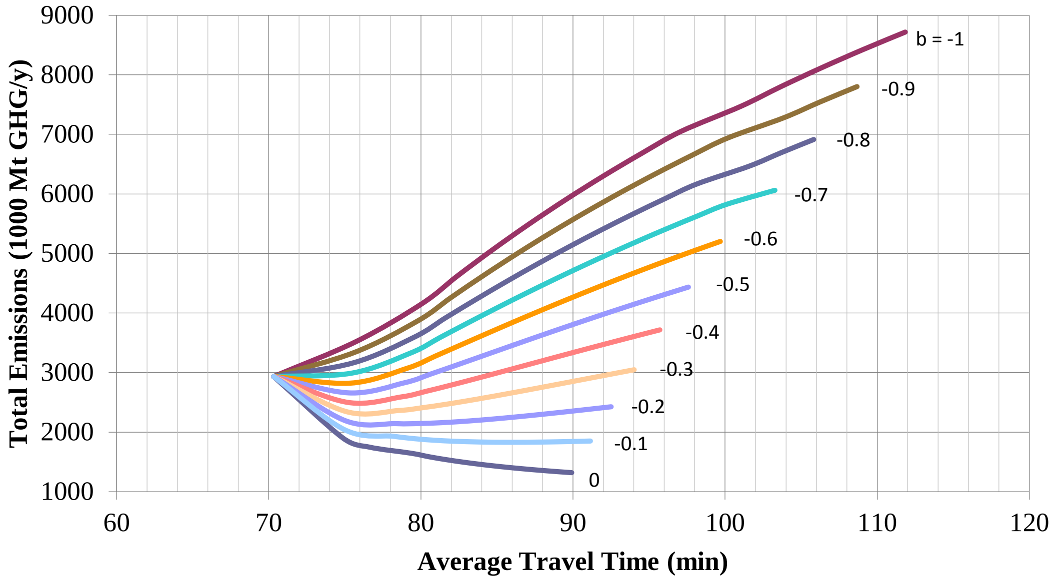
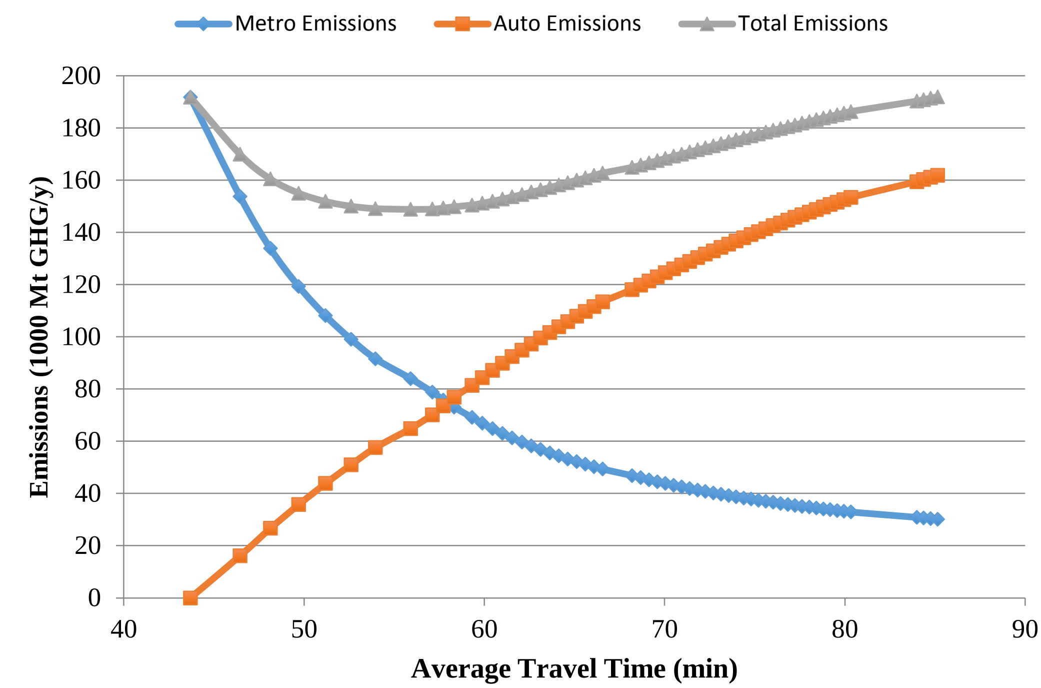
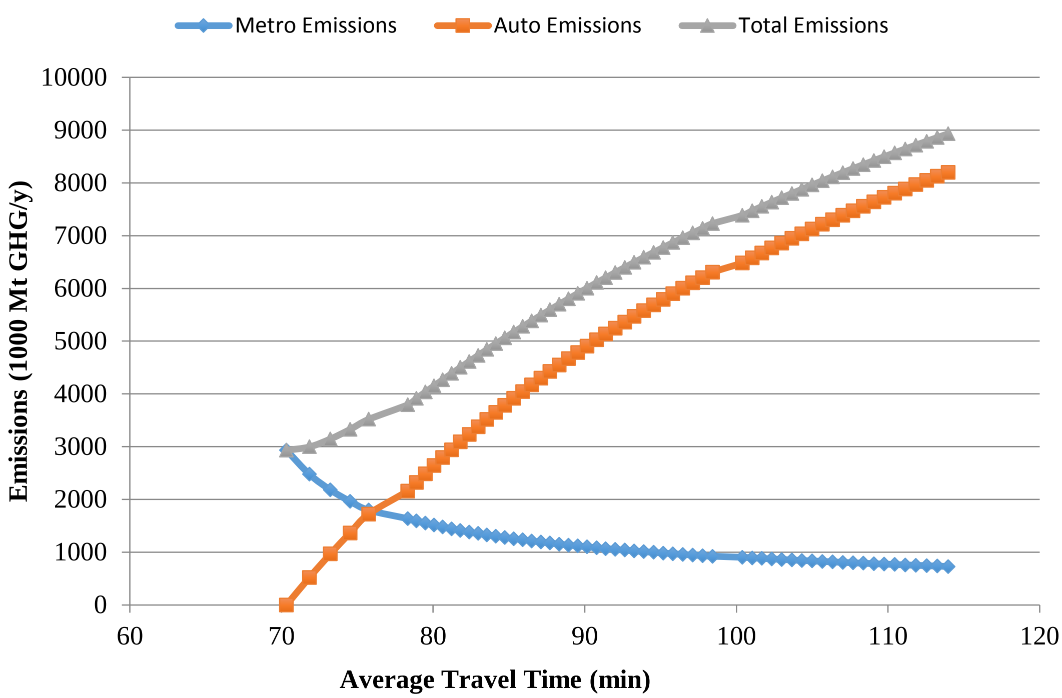


Figure 8 Change in total emissions with travel time as LOS is reduced for metro (scenario 2)

Figure 8 shows the relationship between the total emissions and LOS for a large city (scenario 2). Compared to Figure 5, it is easy to observe the difference that with high elasticity, b = -1 for example, the total emissions increase monotonically as the LOS is lowered from the cost-optimal point. 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, for each individual driver they contribute more auto emissions to the whole society. As the metro LOS is lowered, a large amount of auto emissions are generated from the shifted demand, completely overtaking the reductions in metro emissions. Figure 9 shows the breakdown of the total emissions where we can see the difference between the small city and the large city (scenario 1 and 2).



(a)



(b)

Figure 9 Breakdown of the total emissions of metro (b=-1)

(a) scenario 1; (b) scenario 2

The dominance of auto emissions for large city reflects that large city should rely more on transit in order to save emissions. Figure 10 shows the situation where cities with varying sizes rely either on automobile or metro to cover the entire traffic 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 more transit services are required. However, transit generates much less emissions than automobile especially for large cities, illustrating the "economies of scale" of transit with respect to emission mitigation. This is due to the intrinsic nature of transit that bunches traffic demand into large and flexible groups, making emissions less vulnerable to the increment in traffic demand.

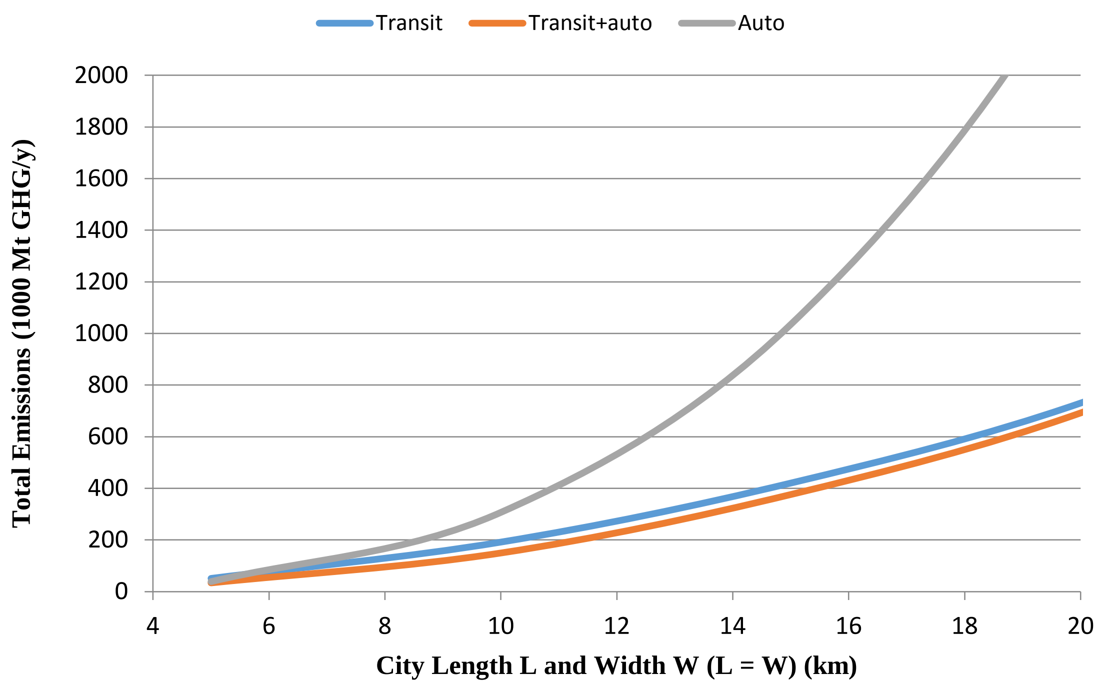


Figure 10 Total emissions of city with varying size

5. Discussion and Perspective

Quantifying the tradeoffs between level of service and emissions can help transit agencies to select the trunk transit technology and optimal network attributes for a new hierarchical transit grid system. Incorporating demand elasticity should be useful to cities and agencies in estimating the emission reductions as a result of reducing LOS.

For small cities, trunk-only bus systems tend to be more cost- and emission-competitive compared with hierarchical transit designs. On the other hand, transit agencies of large cities are more likely to deploy hierarchical transit systems and with mass transit modes such as metro as the trunk technology. Our results are different from the findings in Griswold et al. (2013) where metro was suboptimal in all the city scenarios, which was a limitation of the trunk-only transit model. Incorporating a feeder system increases the relative competitiveness of mass- and capital-intensive transit technology with respect to both cost minimization and emissions savings. Furthermore, for cities that have metro as the trunk mode, the transit agencies may not need to design or operate the system near the cost-optimal point as they would be able to achieve significant emission reductions without incurring large additional societal cost relative to the optimal cost.

Transit demand elasticity would offset transit emissions reduction efforts by incurring 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 LOS while others may not, depending on their trunk transit technology and transit demand elasticity. Transit networks with bus, BRT or LRT as the trunk transit mode should be designed and operated near the cost-optimal point when the demand is highly elastic. Imposing an emissions budget on the entire city instead of the individual agencies is a safer course of action in ensuring emissions reductions. However, transit demand elasticity is a key factor in determining the magnitude of such reduction potentials, which is very important for cities when evaluating the cost-effectiveness of lowering transit LOS. In light of this, agencies should make a thorough investigation of transit demand composition (captive and non-captive users) and flexibility before any LOS-emissions policy is passed. Meanwhile, a city-wide emission budget requires a more robust communication mechanism to be established among different agencies to optimize budget allocation and improve overall system performance, which could be a further extension of this study.

It should also be noted that in reality it is possible for many transit systems to reduce GHG emissions without reducing transit LOS because many of them are not yet efficiently designed to operate at the cost-optimal point. In this situation, the point representing the current costs and emissions of the transit system may be located above the Pareto frontier. Next, we will be studying the actual case of the MUNI bus network of San Francisco. We will quantify the (agency and user) costs and GHG emissions for the current MUNI system and where it falls relative to the Pareto frontier. We will also quantify the potential for total cost reductions for San Francisco if the system were designed optimally to minimize costs, and how the potential might change if GHG emissions constraints are introduced for both the inelastic and the elastic demand cases.

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