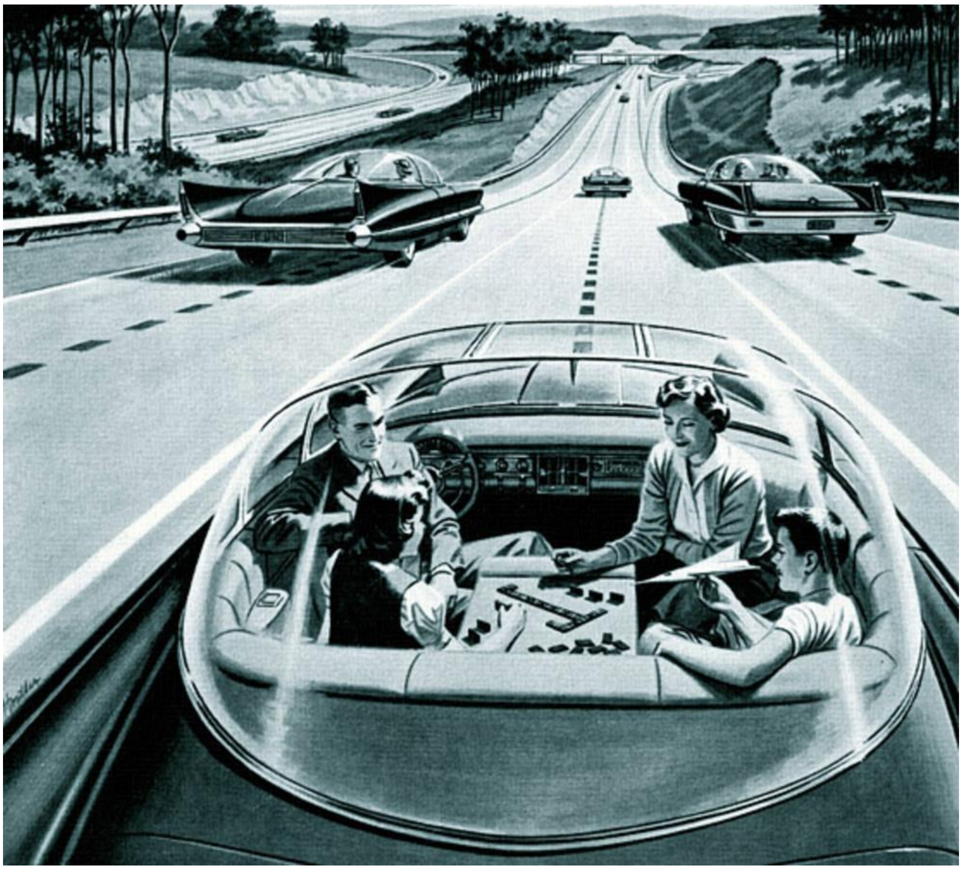


Public Transport Subsidy in AV-Systems

LIU, Jiani

Master Thesis

Spatial Development and Infrastructure Systems

July 2018

Institut für Verkehrsplanung und Transportsysteme
Institute for Transport Planning and Systems

Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

Declaration of originality

The signed declaration of originality is a component of every semester paper, Bachelor's thesis, Master's thesis and any other degree paper undertaken during the course of studies, including the respective electronic versions.

Lecturers may also require a declaration of originality for other written papers compiled for their courses.

I hereby confirm that I am the sole author of the written work here enclosed and that I have compiled it in my own words. Parts excepted are corrections of form and content by the supervisor.

Title of work (in block letters):

PUBLIC TRANSPORT SUBSIDY IN AV-SYSTEMS

Authored by (in block letters):
For papers written by groups the names of all authors are required.

Name(s):	**First name(s):**
LIU	JIANI

With my signature I confirm that

- I have committed none of the forms of plagiarism described in the 'Citation etiquette' information sheet.
- I have documented all methods, data and processes truthfully.
- I have not manipulated any data.
- I have mentioned all persons who were significant facilitators of the work.

I am aware that the work may be screened electronically for plagiarism.

Place, date
ZURICH, 30.06.2018

Signature(s)
刘佳妮
Jiani Liu

For papers written by groups the names of all authors are required. Their signatures collectively guarantee the entire content of the written paper.

Acknowledgements

This thesis is a summary work of my study in the REIS program at ETH.

Future mobility was just a vague term for me two years ago. It looks fancy in Google's advertising commercial but never a real image in my head. Two years study here, especially work with IVT has introduced me to the topic. I did several course projects as well as a semester project on future related mobility topics, including autonomous vehicles, car sharing, etc. It was a great pleasure investigating into those questions. However, the more positive results I got from previous researches, the more I doubted whether there's negative effects. After talking with Prof. Axhausen, the thesis topic has been set to the substitutive good of autonomous vehicle – public transport.

The thesis was quite a challenge for me since it's more of conceptual work instead of data research or model simulation. But Prof. Axhausen has provided lots of valuable insights and inspired me with the important breakthrough points. It has also been a great honor and fun to study with Prof. Axhausen in several courses here at ETH. I would always remember the way to read a literature from the course.

I would also like to thank Thomas Schatzmann. As my co-supervisor, he met with me almost every week to talk through the progresses and obstacles. Especially during the later stage, he devoted lots of time and patience to help me revise the thesis.

Lastly, I would love to thank my parents and friends who supported me in the two years as always. I might not be a perfect daughter or friend, but I'm lucky to have the best parents and friendship.

As an ending note, autonomous vehicles will eventually sort them out, so will life.

Master Thesis

Public Transport Subsidy in AV-Systems

LIU, Jiani
IVT ETH Zurich
Stefano-Franscini-Platz 5, 8093 Zurich, Switzerland

Phone: +41- 78 646 51 37
E-Mail: liujia@student.ethz.ch

July 2018

Abstract

The topic of the thesis originates from the doubts about the current enthusiasm and optimism about autonomous vehicles. One of the possible negatively affected matter by autonomous vehicles could be the public transport according to some researchers and developers. The thesis investigates into the possible impacts of autonomous vehicles on public transport and how public transport subsidy should adapt to the changes. The thesis could be divided into three parts. The first is public transport subsidy theories with case studies in three cities, London, Beijing and Bogota. The second part is the general impacts of autonomous vehicles. In the last part the interaction between autonomous vehicles and public transport and its subsidy. Although different changes could be expected under different scenarios, there is one take-away implication. Autonomous vehicles, especially with car sharing and ride sharing, make the boundary of private individual transport and public collective transport less explicit. Since future mobility is treated as on-demand service, subsidy should also turn to these demand-adaptive services instead of fixed traditional public transport.

Keywords

Public transport; Subsidy; Autonomous vehicle

Preferred citation style

Liu, Jiani. (2018) Transport Subsidy in AV-Systems, *Master Thesis*, IVT, ETH Zurich, Zurich.

Table of contents

List of tables

List of figures

List of abbreviations

AV: Autonomous vehicle

BRT: Bus rapid transit

DRS: Dynamic ride sharing

LBL: London Buses Limited

LT: London Transport

PSO: Public service obligation

OECD: Organization for Economic Cooperation and Development

SAV: Shared autonomous vehicle

SISBEN: Sistema Nacionalde Selección de Beneficiarios

TfL: Transport for London

1 Introduction

Autonomous vehicles (AVs) has been a hot research area in recent years receiving a lot of attention from engineers, legislators, investors as well as the general public. With major technical companies and automobile manufacturers in the world taking part in the revolution, the competition has fostered rapid technology break throughs. As a pioneer, autonomous buses have already debuted on streets in many cities, such as Sion, Stockholm and Beijing. Several highly automated vehicles models are being tested and planned to enter the market in a few years. Fully automated taxis are also expected to enter the market in only one decade by 2020 according to major developers, such as Google. Lots of researchers, even fiction film-makers, start to reasonably envision how travelling with autonomous vehicles will look like in the near future. Many believe that it will become much more comfortable, faster and cheaper to travel in the future, especially when shared mobility becomes mainstream. Such improvements impose greater competition in automobile than public transport travel and makes public transport less attractive. Others believe that autonomous vehicles could offer solutions for the last-mile public transport connection and thus function as a complementary service to public transport. In any way, how public transport service should be offered and structured in the future could be very different from how they are organized now. Public transport subsidy, as an important financial source to offer such service and a tool to adjust the general travel behavior of the society, could be different in future mobility scenarios. Is it still needed? How should it be used? Who should pay for it? Who should benefit? Those questions have never been addressed accurately before.

This thesis will examine the topic of public transport subsidy in a future with autonomous vehicles. The discussion starts with a literature review of public transport subsidy theory, including both its supportive and opponent arguments. The second chapter is a case study with current implementations of public transport subsidy schemes. Three cities with totally different backgrounds, London, Beijing and Bogota, are chosen to illustrate the diversity and complexity of the issue. The next chapter presents an introduction to autonomous vehicles and its technologies. Important terms are explained here for the convenience of the upcoming analysis. Chapter 5 analyzes the impacts of autonomous vehicles comprehensively, including benefits from optimists as well as worries from conservatives. The last part builds up an analytical framework to connect two issues: Autonomous vehicles and public transport subsidy. Based on this framework, these questions are investigated.

There are lots of researches trying to compare public transport subsidy investment in different cities. But the premise of comparison is to confirm comparability that the statistics are in more or less the same scope. Before going deeper into the discussion, it is necessary to first define the concept of subsidy.

In economic terms, a subsidy is defined as a payment by the government (or possibly some private individuals) which forms a wedge between the price consumers pay and the costs incurred by producers, such that the price is less than the marginal cost (Pocket, 1998). In this way, a transport subsidy is defined as all transport costs that are not covered by the users, which includes public investment in infrastructure such as building highways and railways. But it makes it difficult to segregate the public transport subsidy from it. Although some long-distance buses are users of highways, main beneficiaries of highways are automobile and truck users. Passengers and freight transport could both benefit from railways. However, some official statistical bureau doesn’t distinguish between transport subsidy and public transport subsidy, which could incorrectly lead to equalizing the two. Investment in highways facilitate the usage of automobile, which is exactly the opposite of the purpose of public transport subsidy.

In the fiscal policy approach, a subsidy is defined as the economic advantages that are granted from public budgets that do not provide a direct service in return, e.g. grants and tax deductions (EEA, 2007). However, it excludes the payments made to operators to guarantee a sufficient quality of public transport services, which is also known as Public Service Obligation (PSO). For example, service in remote regions with insufficient demand to sustain operation. Because operators do provide service in return in contrary to the definition.

Another kind of subsidy also includes transport related payment by employers to their own employees. Some reimburse the public transport expense, others pay for the parking at the working place et cetera. This kind of subsidy is not covered in this thesis.

To clarify, the term public transport subsidy in the thesis refers to the economic benefits (payment, tax deduction, etc.) offered by the government 1) to public transport service providers to cover the costs induced by the users; 2) to certain groups to improve their affordability or encourage the usage of public transport. A more detailed discussion of types of public transport subsidy will come in 3.4.

2 Public transport subsidy theory

2.1 Rationale for transport subsidy

In economics, subsidy for public transport is mainly based on two classic microeconomic theories: One is scale effects and the other is second best pricing.

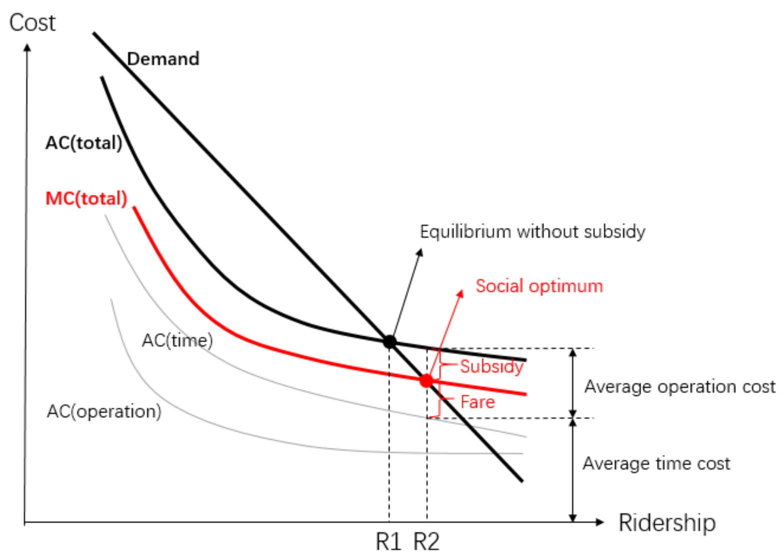
2.1.1 Scale effects

Economies of scale refer to a situation in the production of a commodity, where average total costs decrease with output. A widely applicable explanation goes to the high fixed costs compared to variable cost as well as labor specialization that increases productivity per person. These two effects reduce average cost in output, as the grey downward curve of AC (operation) in Figure 1.

Unlike scale economies of a typical commodity, there's another, more important factor in transportation because of the uniqueness in public transport costs. Apart from operator costs charged through fares, passengers also devote time, as part of their total costs. While reducing in-vehicle time might be difficult, offering more frequent service would directly shorten waiting time for all of the users, supposing that passengers arrive at stations randomly without referring to the operating schedule. It goes similar with reduced average access and egress time when introducing more routes or more densified stations, which is distinguished from economies of scale and called economies of density. People are impatient to wait for a bus that they value out-of-vehicle time much more. So the save in time could be effective enough to keep reducing total average costs even when operation no longer holds economy of scale (Reeven, 2008). Such features in public transportation are called Mohring effects, after the name of the scholar that first proposed such effects (Mohring, 1972). The Mohring effect especially justifies to subsidize short distance services (Nash, Bickel, Friedrich, Link and Stewart, 2002).

As illustrated in Figure 1, with a decreasing average total cost (sum of operation as well as time cost), the red curve of marginal total cost lies always below the average total cost. To realize social welfare optimization, supply should be maintained at the level where marginal cost equals to marginal benefit. Fare level should be set to meet up the gap between marginal total cost and average time cost, which is smaller than the gap between average cost and average time cost, i.e., average operation cost. Operators won't be able to financially survive and will reduce supply, unless a subsidy is offered to help cover the loss (Sullivan, 2012).

Figure 1: Scale effects and subsidy of public transport



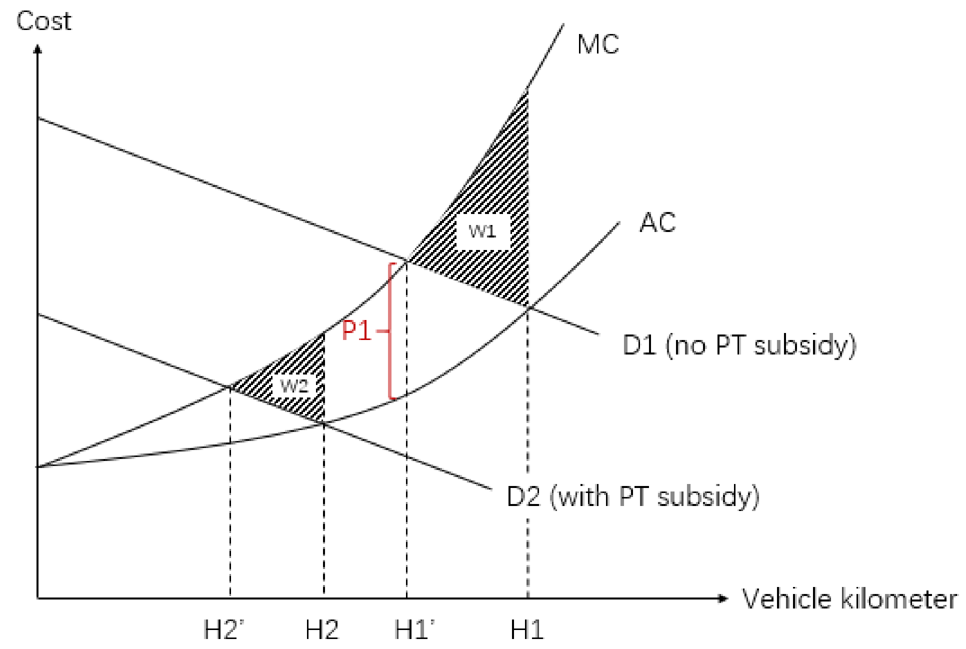
Although not shown in the graph, economies of scale might not hold infinitively. When there's a congestion because of too frequent buses, an even higher frequency reduces average driving speed and increases dwell time so average total time does not hold on to Mohring effect any more (Tirachini and Hensher, 2012).

2.1.2 Second best pricing

The second classic rational for public transport subsidy is to attract automobile users to use public transport through low fare levels, which is called second best pricing.

The pricing of car usage has long been too low to generate optimum usage. As shown in Figure 2, marginal social costs of automobiles (MC) divert from average private costs (AC) due to its large externality such as emission, congestion, noise, accidents, etc. (Sullivan, 2012). There will be an excess usage of H_1 where the demand curve crosses the AC-curve, while the optimal usage should be H_1' where demand curve intersects with the MC-curve. This creates a welfare loss of shaded area W_1. It is optimal to increase the price of car usage by P_1 to meet the gap between MC and AC through congestion fee, road charging, fuel tax etc., which is called first best solution (Else, 1985).

Figure 2: Cost curve of cars in second best pricing



Source: Adapted from Jackson, 1975

Theoretically, it could shift the usage to optimal level and maximize social welfare. However, it's hardly technically and politically feasible to implement such direct control to charge each driver's external cost exactly. Also, because modern economies operate under second-best conditions with distortive taxes on labor, goods and services in place, leading to unequal marginal social benefits and costs in most markets (Small and Verhoef, 2007). Adjustment in the relative costs becomes the second-best solution by decreasing the price of its competitive goods (Glaister, 1974), i.e., public transport.

Lower transit price attracts some people to shift from automobile and reduces the demand for car usage from D_1 to a lower D_2. Similarly, there's still a welfare loss of W_2 since generated usage H_2 is still larger than optimal usage H_2'. Since MC and AC divert from each other more and more, area of W_1 is always larger than the W_2 on its left side. A decreased welfare loss is welfare increasing in this way with value of (W_1-W_2) (Jackson, 1975). The larger the gap between D_1 and D_2 is, the smaller W_2 will be. So, with same amount of subsidy, it will be more effective when the cross-elasticity between transit and automobile is larger.

Changing the price of substitution goods shift demand not only among modes but also across times of day (Parry and Small, 2009). In peak hours, excessive demand of public transport increases delay due to longer boarding time and reduces comfort in vehicles, which are essentially a congestion externality (Else, 1985). While increasing fare in peak-hours is the first-best solution, it might be politically difficult to realize. Reducing fare in off-peak hours becomes the second-best solution to shift travel time in this case (Glaister, 1974; Gwilliam, 2008).

2.1.3 Other motivations

The two classic rationales obviously justify a big part of transport subsidies but only within the scope of economic efficiency. But a governmental financial expense is more complicated than this. Aside from economic reasons, there are also social and political concerns.

From a social view, transport subsidies are justified in cases with poor accessibility, where the subsidy is used to maintain basic transit service and bring social benefits.

In developing countries, good accessibility is an important stimulation to overall economic development. At the first stage of modern China's economic reform in late 1970s, one slogan is "Build a road first in order to develop", which shows the importance of accessibility to alleviate poverty based on the nation's experience. Transport is a complementary input to the obtainment of other social benefits such as education, health services and employment opportunities, among others (Nash et al., 2002; Serebrisky, Gómez-Lobo, Estupiñán and Muñoz-Raskin, 2009). The importance of transport as infrastructure is easier to accepted, however, public transport as service might not be the case among the poor. More debate on it will be addressed in 2.2.1.

In developed countries where transport plan procedures are well regulated, ensuring basic supply of public transport is an obligation of local government. While service in urban center are usually cost-recovery supported by the population density, service in suburban and rural area are more likely to be financially infeasible and rely on governmental subsidy.

Politically motivated reasons justify more cases in developed countries with already basic transit services, where subsidy is the result of a game between different stake holders. Borck (2006) summarized two theories that motivate the officials to subsidize public transport.

The first is capture theory or Chicago theory of regulation: The related industries lobby politicians to subsidize public transport in order to increase their own profits.

The second is based on the voting model: The higher one's income is, the less preferred he is to vote for subsidy due to its accompanying higher tax rate. Because public transit is assumed to be price inelastic so that the rich benefits less from a lower transit fare, but a high tax rate reaps more money from them than from the poor. So, in a society where median income is lower than mean income, high-income people become the minority group and the voting result tends to result in a lower transit price and a higher tax rate.

2.2 Controversy of transport subsidy

Even with various arguments to support the subsidization of public transport, there are always concerns regarding its inefficiency or even negative effects. Compared with the two classic rationales which start from the nature of the subsidy itself and suit most cases generally, the controversy of transport subsidy is more case specific. They should be addressed in each policy separately, but are not always checked ex ante. It might not be easy to answer whether they apply to the specific case or not either.

2.2.1 Cost efficiency

A subsidy is not cost efficient when it costs too much, either compared with its original budget, or compared with alternative policies which would have generated similar improvements.

The first has been criticized a lot when the subsidy amount keeps rising after an authority started subsidizing public transport. At the same time, other output indicators such as passenger kilometers and ridership numbers show a smaller growth than expectation. The total amount of subsidy to public transport systems in the United States (U.S.) in 1980 increased by 15 times compared to the value 10 years ago (Pucher, Markstedt and Hirschman, 1983). At the same time, labor productivity in vehicle-miles per employee dropped by 16 percent (Cervero, 1984). Such contrast intuitively gives the impression that subsidy is inefficient. Widely recognized, an increased cost is related with transport subsidy, and cost increase is largely due to labor cost increase (Small, Verhoef and Lindsey, 2007), or a waste of resource such as higher scrappage rate and shorter life span of buses (Frankena, 1987). The effect is especially large in a transport system protected from competition. For example, every 10 percent increase in the proportion of cost covered by subsidy is accompanied with a 5 percent increase in total cost from 1975 to 1981 in Britain (Rye, 2008). However, causal relationship is more complicated than correlativity. Cervero (1984) used data in California to conduct a pooled time series and found a general negative impact of subsidy in cost and performance, but only modestly. He found that impacts are stronger in operation costs than in productivity and efficiency, e.g., vehicle-mile per vehicle. This is somehow opposite of observations in lower vehicle life span from Frankena (1987). He also found that local subsidy tends to work in a negative direction while federal subsidy tends to generate positive effects. Nevertheless, subsidy, cost, service level and fare are somewhat interdependent (Pucher et al., 1983). Subsidy may increase cost but at the same time increase service level and reduce fare level. Such factors need to be controlled to make a conclusion.

Another inefficiency comes from capital bias. With subsidies, capital is willing to build more infrastructure and offer more service to increase economic return. However, there might not be sufficient bundled demand for such service and subsidy is used to build up wasted capacity. For example, it’s believed that local governments, at least in US, are encouraged to build rail systems with extremely overpredicted demand (Small, Verhoef et al., 2007). On the other hand, local governments might argue that they subsidize transport infrastructure to stimulate local economy, while some researchers doubted the efficiency of such stimulation. For example, Taylor and Samples (2002) studied the case in southern California and found out that capital subsidy generates overall less employment than operational subsidy in transportation.

Similarly, subsidizing transport in developing countries to alleviate poverty also faces the question of more efficient alternatives. The poor needs to be subsidized not only in accessibility, but also food, education, etc. One might question why not directly increasing their income could bring an extra degree of freedom to increase welfare. A case in Brazil shows that many people sell their transport vouchers instead of using them themselves (Serebrisky et al., 2009). Although there’s no wasted resource, the same effect could be reached with more efficient approaches.

2.2.2 Redistribution effect

The redistributing effect is generated inevitably when different groups of people benefit differently from the policy, as well as contribute differently to the financial source of the subsidy. Tscharaktschiew and Hirte (2012) summarized possible discrimination among subsidization policies in Germany, including travel purpose, travel modes, employment status, income level, monetary- or time-based charging. For example, some subsidies only favor commuting over others like leisure. Most redistribution analysis distinguishes between the rich and the poor group. But there are different conclusions for different schemes.

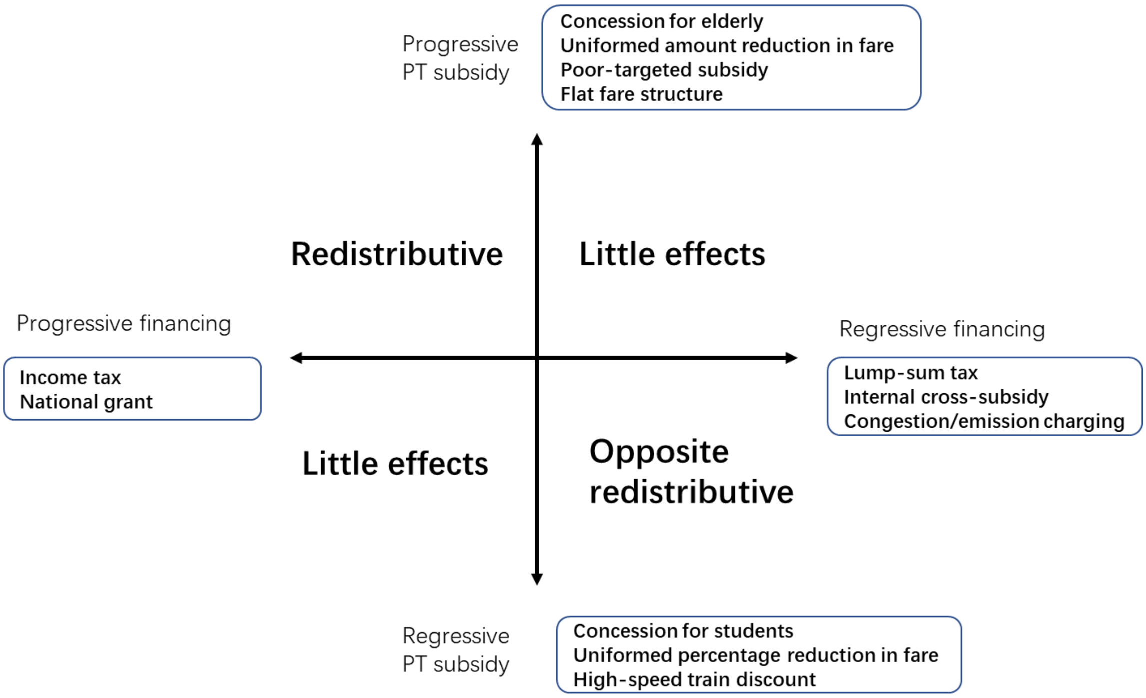
For subsidies per kilometer, people with longer travel distance benefit more from this kind of schema (Borck, 2006). Considering only commuting trips, if the residential location pattern turns out to be the American case, rich people who live in suburban areas benefit more than poor people in the city with much shorter commuting distance. But in most European cities the rich live closer to the center, e.g. in Paris (Brueckner, Thisse and Zenou, 1999), so the poor turn out to benefit more in this case.

Such analysis is based on a simplified prerequisite that all people face the same mode and same commuting cost function, which is not always satisfied in real cases. The rich usually hold a higher value towards time and are willing to invest more for higher speed and more comfort (Borck, 2006). On the one hand, rich people tend to prefer automobile to public transport thus benefit no more than a relieved congestion because of those former-drivers who shift towards public transport. On the other hand, when the subsidy is not flat per distance but a fixed percentage of the total costs, rich people who spend more per unit would benefit more in absolute value. For example, a universal 20 percent discount for all train connections for season ticket holder saves more for first-class high-speed train users, who are more likely to be rich.

The net result might shift once again if financial contribution is considered. For lump sum taxes, the poor lose relatively more, while the rich contribute more when it’s income tax funded (Borck, 2006; Tscharaktschiew et al., 2012).

The redistribution effects of public transport subsidy are summarized in Figure 3. A financing is considered regressive when it asks more from the low-income group, such as all kinds of flat charging. Specifically, in the transport field, congestion and emission charging are usually considered to be regressive, since they charge the same amount for each individual which affect low-income group more. A subsidy is considered to be regressive when it benefits low-income group more, such as a subsidy to support concession for elderly (Gwilliam, 2008). Among all elderly people, those from low-income group tend to use public transport more than those from high-income group. Similar explanations go for the analysis of student concession fares, just that the conclusion is opposite. Other examples are offered in the boxes for each of the four types. However, the categorization allows exceptions. For example, internal cross-subsidy is categorized to be regressive because usually it is the low-income area that have sufficient demand for public transport to operate with profits and support the operation in low-density high-income area. But the situation doesn't hold all the time so it could also be on the opposite side of the axis.

Figure 3: Redistribution effects of public transport subsidy



A combination of progressive financing and progressive subsidy will realize redistribution between the rich and the poor. For example, using national grants to offer public transport coupons to low-income people. Using revenues from congestion charging to support a uniform amount of fare reduction could have a little redistributive effect since it benefits low-income public transport users by worsening low-income automobile users. Public transport subsidy schema could even be on the opposite direction of redistribution when both the financing and usage are regressive. For example, when congestion charging revenue is used to support student concession.

Secondary effects, which are long term, are not addressed by Figure 3. Access to public transport can raise land and property value remarkably, especially subway and bus rapid transit (BRT). Developing countries, which are currently investing largely into such constructions, usually start from urban centers that are also high-income area, favoring rich people. Some researches involved further landowners as another group in the redistribution analysis. With cheaper transits, people have the incentive to live farther from city center, which would decrease the rent in the city and increase the rent in suburbs. The overall effect is that aggregate land rent is decreased and landowners as a whole will be worsened off (Borck, 2006). Since landowners are more likely to be from the rich group, it's also a factor to discourage them from voting for subsidy.

Nonetheless, public transport subsidy usually doesn't make up a large proportion of the government expenditures. No matter the net result increases the well-being for the rich or the poor, the redistribution effect is relatively small (Frankena, 1973).

2.2.3 Spatial effects

Spatial effects can be analyzed using two well-known models. The first one is the monocentric model, which explains urban sprawl in a single city as a result from lower transport costs. The second one is the core-periphery model, which explains possible agglomeration or dispersion equilibria in a two-region setup under consideration of different transportation costs.

2.2.3.1 The monocentric model

A monocentric model is often used to explain sprawl effects (Figure 4).

In a monocentric city, urban residents utilize through the consumption of housing and other goods, under the budget constraint of income and commuting costs.

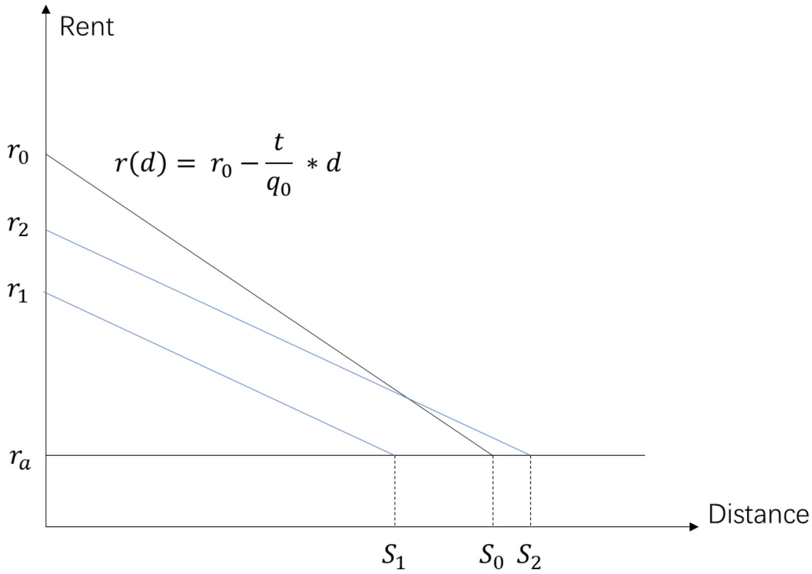
$$r(d) * q + c = y - t * d \quad (1)$$

(r(d): unit rent at location d; d: distance to city center; q: housing size; c: other goods; y: income; t: transport cost)

Suppose size of housing area is fixed at q_0 for everyone, rent at city center is given as r_0 and price of other goods are set as 1, consumption of other goods at city center could be derived.

$$c_0 = y - r_0 * q_0 \tag{2}$$

Figure 4: Effects of transport subsidy on city size



Since all residents in the city are indifferent in utility, such consumption of (q_0, c_0) should apply to everyone, which gives the housing rent for each location using equation 1.

$$r(d) = r_0 - \frac{t}{q_0} * d \tag{3}$$

The city size is then decided where rent for urban housing equals to the rent for rural agriculture r_a, which is set to be constant in the model, i.e., S_0 in Figure 4.

The effects of transport subsidy can be seen on two sides (Brueckner, 2003). People in the city now face a new budget constraint. Not only is the transit cost smaller, but also the disposable income is because an added tax (T in Equation 4) usually needs to be paid to fund the subsidy.

$$r'(d) * q + c = y - T - t' * d \tag{4}$$

Suppose that the consumption of (q_0, c_0) still holds so that nobody is better or worse off than before, rent in city center will decrease to (y-T)/q_0. At the same time, the transit becomes cheaper, so the slope of the bid-rent curve becomes smaller. As shown in figure 4, these two changes could lead to two different sizes of cities. One is smaller, the other is larger, depending on the relation of added taxes and reduced travel costs. Brueckner (2003) derives the equation for tax and lower transport cost, i.e., sum of total tax should cover the sum of decreased transport cost for everyone. However, the symbol of change in city size is still unclear. The only conclusion is that when cost starts changing slightly from t to t', the result is larger urban sprawl. Such dominance of expansion effect is stronger especially if the subsidy gets to be partly supported by transfer from federal government because less local head tax is levied. Su and Desalvo (2008) investigated subsidy in public transport and automobile separately. They first conducted a comparative static analysis and then used empirical data from 201 quasi-monocentric U.S. cities for a regression analysis. Two results lead to the same conclusion that urban area expands with an increase in auto subsidies but shrinks with increase in public transport subsidy.

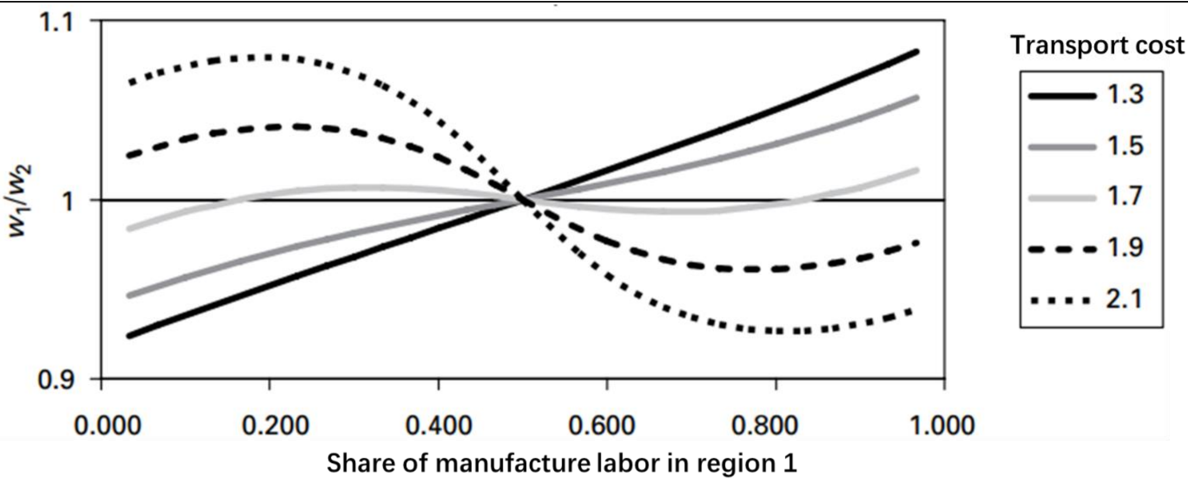
In the monocentric model, the spatial growth of a city is inefficient because it consumes more land and affords more traveling to reach the same utility level for same amount of population. However, city growth itself is not the evil and there is no right answer regarding the best size of city. When two cities are considered, low regional transport costs could encourage concentration to one of them and bring further benefits of agglomeration.

2.2.3.2 The core-periphery model

Krugman (1991) developed the core-periphery model in the early 1990s to analyze the location of industrial activity in a two-region context. An agriculture and a manufacturing sector as well as two regions are assumed. The spatial allocation of agricultural activity is exogenously given. The manufacturing sector produces under increasing returns to scale and is modeled by means of the Dixit-Stiglitz model of monopolistic competition. Only labor in the manufacturing sector is mobile and migration happens when there is a difference in real wages (nominal wage deflated by the price index). Wage in agriculture is set to be 1 for both regions so what matters is the nominal wage in manufacture and the price index. Only transport costs in manufacture exist and are represented in the form of iceberg costs. Every T unit of goods sent to another region becomes 1 unit, while the foregone (T-1) unit is used to pay for transport cost as if the iceberg melted during transportation. When the cost equals 1, it means transport is free of costs.

Given the initial distribution of labor, i.e., the ratio of labor in two sectors and two regions, the total income can first be derived as function of wages in manufacture in each region. The price index is derived using Dixit-Stiglitz model (1977) and is a function of the share of labor in manufacture, wages in manufacture and an exogenous substitution parameter between goods. The third step is to compute the wage level that the manufacturing firms are able to pay concerning the price and production. The wage level is a function of income, price index, transport cost and the substitution parameter. Last, the real wage for two regions could be solved using the set of equations from these steps. Although they can't be derived as a simple closed formula, Brakman, Garretsen and van Marrewijk (2009) simulate the functions using computer power to show the result for different scenarios. After setting the value for all exogenous parameters and the share of immobile agriculture labor in both regions, different long-run equilibria can be derived under different initial manufacture labor distributions and transport costs (Figure 5). Transportation costs refer to different obstacles to trade between regions, such as tariffs, language, culture barriers and obviously the costs of getting goods or services at another location. Furthermore, real wages and welfare implications for each group as well as aggregate welfare changes can be explained by this model.

Figure 5: The impact of transport costs in the core periphery model



Source: Brakman et al., 2009

Suppose manufacture labor are initially equally distributed between two regions, the real wage in both regions are equal and nobody has the incentive to relocate. Such equilibrium is not stable for low transport costs (1.3 and 1.5). Once a small amount of labor relocates to region 1, the real wage ratio between region 1 and 2 increases to be larger than 1. The wage difference becomes larger and larger, which keeps attracting migration until all labor is concentrated and the long run outcome is agglomeration in region 1. The same principle holds for region 2. Whoever wins a little more labor in the first place will get the advantage accumulated and becomes the agglomeration core in the end. However, the dispersion equilibrium is stable in the high transport cost scenarios (1.9 and 2.1). For intermediate transport costs as for the case 1.7, 5 equilibria can arise. Two unstable ones where the cost curve crosses the real wage line and three stable ones, two agglomeration equilibria and one dispersion equilibrium. To conclude, higher transport costs increase the likelihood of a dispersion equilibrium further as there is a higher real wage difference for a given value of lambda. Lower transport costs then result in a decreased likelihood of dispersion equilibrium. The economic interpretation of this is that the higher transport costs effectively make two regions further apart.

It is beyond the scope of this thesis to discuss real wages and its implications for aggregate welfare in detail, because it depends on initial conditions as described above and many simulation runs. Nevertheless, it is worth it to mention that transport costs influence where the long run equilibria will occur in the core periphery model. The core model gives rise to different policy implications. One is that temporary policies, subsidy for instance, can have permanent effects on the equilibrium spatial allocation of economic activity.

3 Implementation of PT subsidy: Case studies

Rationales for or against public transport subsidy diverse so much that no studies have encompass all of the complication in a real-world case. And academic research results could be opposite regarding a same case (Parry et al., 2009; Small and Verhoef, 2007). No matter how controversial it could be, public transport subsidy is ubiquitous for a long time, especially in developed countries (Serebrisky et al., 2009). There's no global unified statistics to measure the accurate number of subsidies. Alternatively, several researches computed farebox cost-recovery ratio to approximate the subsidy needed to cover the deficit. The European Commission's UNITE project computed cost-recovery ratios averaging 50 percent for 10 European nations in 1998, varying from 25 percent for Italy to 91 percent for the Netherlands (Small and Verhoef, 2007). Note that it's only approximation because operators have other source of revenue other than farebox, such as selling advertisement, renting out properties, etc. What's more, some costs are discounted or even exempted for public transport operators, which are essentially a form of subsidy that will not be recognized using farebox cost-recovery ratio.

The success of a transport subsidy program depends not only on the optimal amount but many other factors too, e.g., the form of subsidy, the structure of operator, and its relationship to the subsidizing body (Else, 1985). There's never a universal answer in an optimum level of subsidy, which is why transport subsidy policy can only be assessed case by case.

In this chapter, three cases in cities with different backgrounds (London, Beijing and Bogota) are analyzed. London is a typical densified western city with already relatively integrated public transport network. It's also famous for its bus deregulation history and offered experience in bus tendering. Beijing is chosen for its huge achievement in rapid public transport network expansion and densification in recent decades. Many newly developing countries all face a same process to improve their poor infrastructure in transport. Beijing is famous for its efficiency of process in time but also inefficiency in financial investment. However, such trade-off has stimulated the rapid growth of the city and is not simply waste of money. Bogota is chosen for its successful experience in BRT development. Same as a metropolitan in developing country, Bogota is different from Beijing in its limited budget both from the government as well as from the users. The government can't afford huge subsidy burden as Beijing to support low fare level.

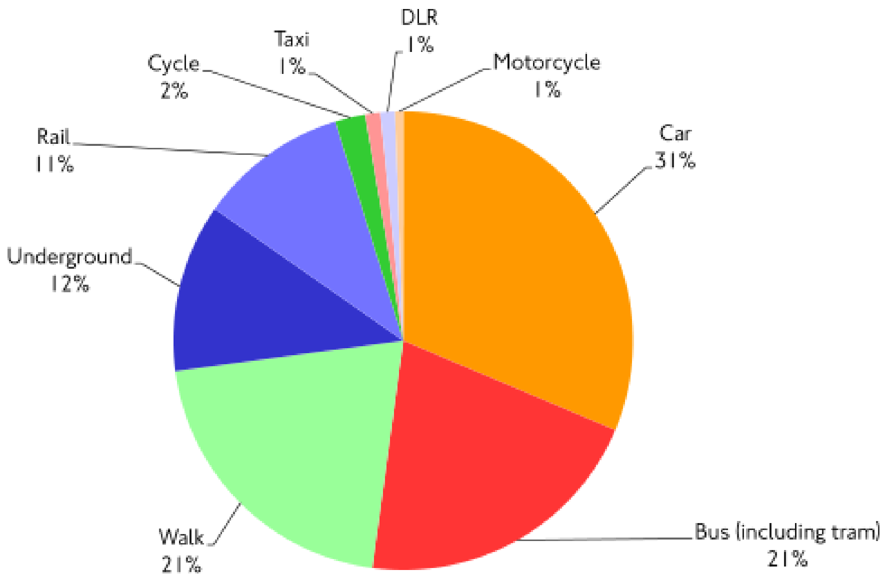
Large number of users thus can't afford the high fare level either. However, it succeeded in making the whole business financially sustainable.

Three cities differ a lot from each other in their background as well as subsidy program. A comparison is summarized in the end of the chapter to illustrate such difference and derive some take-away implications.

3.1 London, UK

Transport for London (TfL) is an integrated transport authority led by the Mayor of London, and is in charge of most of the public transport services in London, including London Underground, London Buses, TfL Rail, etc. Among them, bus (including tram) is the most frequently used public transport as shown in Figure 6, still after car though. The red London bus not only forms one of the classic images for the city as well as one of the most important services for its residents, but also offered valuable insights into public transport financing with its own experience.

Figure 6: Modal split of daily journey stages in London, 2015.



Source: Transport for London, 2017

Britain started its nationwide bus deregulation process in 1986, but London was left out and underwent its specialized London Regional Transport Act 1984. The government took a relatively conservative step in the capital metropolitan and introduced a system of competitive tendering for route services to reduce costs, increase service quality and maintain constant fares (Kennedy, 1996a). London was seen to some degree as a control group for the national privatization experiment, though London might be too different from other areas to be a representative control group (White, 1995).

Before 1984 the bus service was solely operated by a publicly owned and subsidized company London Transport (LT). After the Act LT introduced an operational subsidiary London Buses Limited (LBT), which was later split into 13 local subsidiaries. While route planning and fare structure were still under the control of LT, competition for operation happened between LBT and an emerging group of private operators. At the beginning, only a small number of routes in the periphery were tendered, in order to facilitate the private entry into the market. The tendering process was accelerated after LBTs started its privatization in 1994 (Cantillon and Pesendorfer, 2005). Control over the bus services were shifted several times between the central government and the local government and is now led by the Greater London Authority (GLA) (Amaral, Saussier and Yvrande-Billon, 2013). By 2001, all bus services in London were operated by private operators under tendered contracts. At present, the contracts are signed with London Bus Services Ltd (London Buses), a subsidiary of TfL. London Buses plans bus routes, specifies service levels and monitors service quality. Besides, an independent official watchdog London Transport Users Committee, also known as London TravelWatch (LTW) exists to represent users' interest, although it's funded by GLA (Transport for London, 2015).

There used to be two different types of contracts, gross cost contracts and net cost contracts. Their difference mainly expresses the different risk allocation between operator and the authority (Boitani and Cambini, 2006). Under gross cost contracts, the revenue is collected for the authority, while under net cost contracts, the revenue goes to the operator. Gross cost contract can ideally test the lowest cost in the market under the given service level, but it also requires a strong authority to guarantee the revenue collection. Net cost contract distinguishes between profitable and unprofitable routes and only subsidize unprofitable ones. It offers more incentive for operators to increase quality and then increase ridership and revenue, but it also tends to result in higher subsidy since the operators tend to be conservative regarding revenue estimation to reduce its own risk. Which one is more advantageous is always under debate and should be answered case by case (PPIAF, 2006). Starting 2001, TfL introduced the quality incentive contract to replace the former two types (Transport for London, 2015). It’s an extension of gross cost contract in its nature since the revenue goes to TfL. It’s an improvement in the sense that it offers financial incentives for operators to improve performance. The contract specifies a Minimum Performance Standard (MPS) regarding the service quality and a base contract payment. There would be payment bonus or deduction when the service is offered above or below the standard.

In 2017, the subsidy to London Buses amounted to £655 million, which was 30 percent of all expenses (TfL, 2017). The subsidy comes from a wide range of sources. There’s National Concessionary Fares Scheme to subsidize discounts for disabled and elderly people. Department for Transport (DfT) offers fuel tax rebate under the Bus Service Operators Grant. Revenue from congestion charging goes to TfL and could also be transferred to support bus operation. Lastly, TfL receives budget from GLA to sustain the bus services. Back in 1984, subsidy amounted to £180 million (Kennedy, 1996a), and in 1985 farebox covered 60 percent of all costs (Hensher and Wallis, 2005). The net total change might seem discounted because of increase in total kilometers run (White, 1995).

The success of competitive tendering scheme in London bus operation is widely recognized, in cost reduction, revenue gains and welfare gains to passengers (Kennedy, 1996b). However, most studies only observed changes in the first decade of bus tendering and lots of indicators experienced a turning point in 2000 (Preston and Almutairi, 2013). Different figures were obtained regarding cost saving when researchers compared the change at different time slots. Kennedy (1996a) calculated a 14 percent net cost saving over the period 1987-1992. White (1995) estimated a reduction of 35 percent from 1985 to 1994. The largest reduction comes from Hensher and Wallis (2005) which amounts to a 51 percent unit cost reduction from 1985 to 2000. The reduced cost usually comes from three main sources: reduced factor prices such as lower wage, reduced use of factors such as fewer employee, and improved production processes such as vehicles of more appropriate size. Among these, labor cost is recognized as the most important cost saving since it accounts 70 percent of total cost (Kennedy, 1996a). However, it’s also noticed that cost tends to increase back later on during re-tendering processes (Hensher et al., 2005), which explains the increase in London after 2000. Generally speaking, competitive rendering is estimated to reduce cost by 20-30 percent using statistics from different cities (Hensher et al., 2005). Such figure also fits the statistic of London in the long term.

Bus tendering has also encouraged better service and increased demand. The service level is specified in the contracts and the operators must fulfill the promised schedule to receive full amount of subsidy, which provides incentive for operators to maintain the basic service level. In reality the actual miles run by the operators are usually smaller than the schedule promised. The ratio of the actual mileage in the planned mileage could be an indicator for service level. The larger the ratio, the higher the level, because it shows the reliability of the service. It is found that between 1987 and 1992, ratio in tendered routes are always higher than those not tendered (Kennedy, 1996a). Taking the gap between these two groups as the improved service resulted from bus tendering, the increased revenue could be estimated using demand elasticity on mileage. The result is that tendering brings extra revenue of £9.6 to £71.6 million (Kennedy, 1996b). As for long-term trends of demand, London has experienced general increase after bus tendering, while demand in other areas in Great Britain have been constantly dropping. 36 percent of the demand decrease is believed to be caused by the bus deregulation (Preston et al., 2013).

Aggregating the producers' surplus increase because of higher demand and lower cost, as well as consumers' surplus increase due to higher quality, bus tendering in London is believed to be increasing social welfare as a whole, although absolute value of subsidy isn't decreasing compared with 1985. Kennedy (1996a) estimated the total welfare increase in 1987-1992 to be £90-380 million. Preston et al. (2013) assessed the policy in longer term and found a welfare increase of £3314 million to 2005. Compared with deregulated area, the average benefit per person in London is 5 times stronger. While the deregulation in other areas is showing more problems especially in the long run, the tendering policy is clearly beneficial (White, 2010).

3.2 Beijing, China

Things are different in Beijing in a sense that public transport in Beijing was more determined by the government. There are 4 main operators, 3 of which are owned by the state (2 in charge of bus operation and the other one for 15 rail transit lines), and the last youngest one is in joint venture under PPP (Public Private Partnership) operating 3 metro lines.

The subsidy is in block grant including both capital and operational assistance. The amount is based on the negotiation between government and operators. The operators make budgets for the year and apply for a certain amount of subsidy. The government then decide the amount to grant. But it has been criticized a lot regarding lack of transparency of the process. Not only is the public kept away from the negotiation process, but the government is also to some extent kept away from the real operating cost. The operators are required to publicize the cost of the past year before late October for at least a month[1]. But no such publication can be seen during the writing of the thesis. The costs are only expected to be reported in rather aggregated way, without distinguishing profitable and unprofitable lines, peak and off-peak loads, etc.[2], which makes the verification of subsidy amount applied difficult. The publication for governmental financial affair is also not in detail enough. Only total expense for the whole transportation industry is publicized in official yearbooks. Subsidy specific for public transport operation is only publicized in 2010, 2013 and in a 7-year average value from 2007 to 2013 from press conference. Based on the proportion of these 2 pieces of data, the subsidy is extracted from the total transportation expense on a 90 percent base, shown in Table 1.

Table 1: Public transport volume and subsidy in Beijing (2006 – 2016)

Year	Passenger trip (million)		Network length (km)		Transport subsidy (billion)	Percentage of total public expense
	Bus	Rail transit	Bus	Rail transit		
2006	3979.19	703.06	18468	114	0.6345	0.489
2007	4226.45	654.93	17353	142	2.9781	1.805
2008	4708.63	1216.6	17857	200	7.2315	3.691
2009	5165.17	1422.68	18270	228	13.236	5.707
2010	5051.44	1846.45	18743	336	13.949	5.133
2011	5032.72	2192.8	19460	372	17.921	5.522
2012	5154.16	2461.62	19547	442	21.938	5.953
2013	4843.06	3204.69	19688	465	20.861	4.998
2014	4771.8	3386.68	20249	527	19.31	4.268
2015	4060.03	3323.81	20186	554	26.607	4.637
2016	2690.19	3659.34	19819	574	31.813	4.966

Source: Beijing Year Book (2017) http://www.bjstats.gov.cn/nj/main/2017-tjnj/zk/indexch.htm

There are several things worth notice.

[1] Beijing Municipal Commission of Development and Reform, 2015 http://www.bjpc.gov.cn/zwxx/zcfg/xcwj/zcwj/201512/t9819811.htm

[2] http://www.bjpc.gov.cn/zwxx/zcfg/xcwj/zcwj/201512/P020151231540723570842.pdf

First of all, the subsidy amount has changed dramatically since 2007 from 0.6 to 3 billion, which is because of the sharp pricing reform. The public transport was set to an extreme low price in that year to encourage mode shifts and reduce road congestion. Rail transit was priced at only 2 RMB (1 RMB = 0.13 Euro) per trip regardless of distance[3]. In 2013, the ticket revenue only covered the operation cost for 21.8 percent (rail transit) and 15.6 percent (bus) per passenger kilometer[4]. The subsidy increased nonstop to be a huge financial burden after a few years along with the increase in both passenger volume and network length.

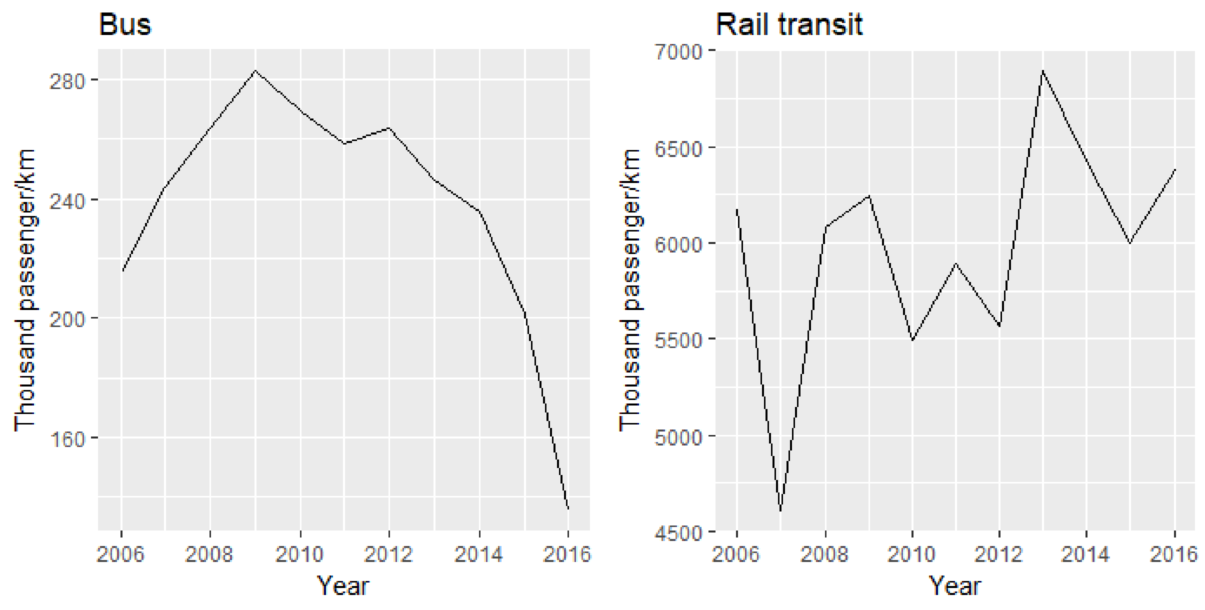
In 2014 the public transport experienced a rise in pricing. Currently, both fare increases with distance. Weighted by the average travel distance, the fare for rail transit increased for 132.6 percent and bus 159.3 percent. Still government pays for 50 percent and 70 percent of the operation cost for rail transit and bus per kilometer trip[5]. However, following the pricing reform in 2014, transport subsidy didn't decrease at all, especially in absolute value. It's under the expectation by financial bureau though, since subsidy for public transport will go more into infrastructure construction, bus replacement and smart transport development after 2015.

Secondly, the network has been expanded and densified for the past decade, which is an important reason for government to subsidize public transport. The effect of fare level change in public transport usage, has to be separated apart from the usage increase induced by network expansion. A simple estimation is conducted using demand divided by network length, i.e., passenger per kilometer of rail or bus route, or demand density. It's only a rough approximate to eliminate density effect since no frequency information is available. Nor does demand increase linearly with network density. It could only roughly imply how passengers demand for public transport changes with fare level. As shown in Figure 7, bus is losing its attractiveness despite densified network and low fare as early as 2009. Rail transit fluctuates more but keeps at a relatively balanced value of 6 million per km. It's interesting to notice that the effect of pricing changes is remarkable instantly, however always rebounds in a few years. This shows that the intent to increase attractiveness through low fare isn't efficient in Beijing case. People

[3] As a reference, the disposable income per capita in Beijing, 2007 was 21989 RMB.
[4] Beijing Daily, http://www.gov.cn/xinwen/2014-10/27/content_2770815.htm
[5] Beijing Finance Bureau, https://www.baidu.com/link?url=GFp9IBhCmyNVEM3nvQM77T1pe3Jvo9nbjnG5iNuOM_B3AT9e5iQ8BzGq2TMf9MlFIAHVu3ZSMvFoFeq-lgD6WQPLo-L4HxZVWpWvxDnAvpO&wd=&eqid=b78257d400034233000000065ab9e253

could be sensitive to price change in a short period, but would get used soon and re-adjust their behavior. The increased usage is mainly due to increased service scale. It's been criticized that the low fare only shifted pedestrian and cyclists to public transport because mode share for automobile didn't change a lot after low pricing era and congestion isn't relieved (Zhou, Murphy and Long, 2014). Congestion makes bus delayed, which further reduces attractiveness of public transport.

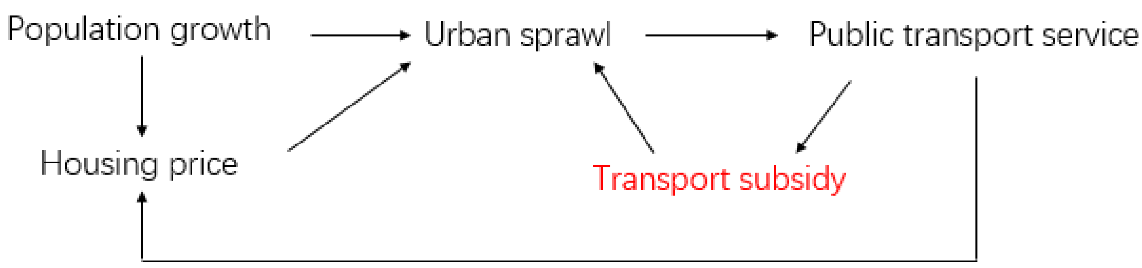
Figure 7: Demand density in public transport, Beijing



Source: Self illustration based on Beijing Year Book (2017)

Lastly, all the increases in Beijing (passenger volume, public transport network length, etc.) have to consider the contribution of urban growth, both in population increase as well as spatial sprawl. Population keeps growing because of the centrality of the capital city. New citizens with low- and middle-income are priced out in housing market and could only live in the suburban area. This drives urban sprawl (Zhou et al., 2014), from the demand side in the first place. These new housing are largely scattered, low-densified, informal habitats equipped with poor infrastructure and public transport access, which increases commuting distance and encourages car travel (Zhao, 2013). While higher density promotes public transport travel, provision of public transport also requires basic density level (Zhao, 2010), otherwise large amount of subsidy is required. Whenever public transport access is planned, housing price increases quickly even before its implementation (M. Zhang, Meng, Wang and Xu, 2014), which further encourages pricing-out process. What's more, the financial source comes largely from land revenue instead of tax revenue in China. To cover the subsidy needs of urbanization, local government tends to sell more lands in the suburban area, which forms urban sprawl in the supply side (Zhao, 2010). The belief in population growth and transport network expansion encourages the enthusiasm in land market which increases housing price (Zhao, 2011). The poor has to live even further from city center, aggravating the urban sprawl from demand side. Once again, the government needs money to offer new transport infrastructure in the further suburban area. As shown in Figure 8, Population, housing, urban sprawl and transport subsidy keep encouraging each other to grow and it's hard to determine whether it's A encourages B or B requires A. The efficiency of subsidy solely in transportation is inefficient economically. However, the whole chain reaction of externalities makes it complicated to judge comprehensively. Since the population is expected to continue increasing, such interaction would continue to play a role unless further actions are taken.

Figure 8: Urban sprawl and public transport in Beijing



3.3 Bogota, Colombia

In other developing countries, government can't always afford subsidy as large as Beijing. What is implemented is usually a targeted subsidy to be more financially sustainable. A case study of Bogota, Colombia is conducted to illustrate subsidy in this situation.

Bogota is famous for its BRT system starting in operation since 2000, TransMilenio. Apart from it, there's another conventional bus system called Buseta. Two systems are parallelly operated and are independent from each other. On a trip based calculation, private car only counts up 15 percent in all modes, while two bus systems make up 57 percent, much more on Buseta (74 percent) compared with TransMilenio (26 percent) though (Kaufmann, 2012).

TransMilenio network has been implemented in stages. The system was planned to eventually reach 390 km in 2031 and cover 80 percent of the travel needs (Gilbert, 2008). According to BRT Data in 2014, there are 11 corridors with a total network length of 112.9 km in a city area of 1587 km^2, with overtaking lane on most of the routes and all stations. While 117 trunk lines run on the corridors, there's another complementary system of 107 feeder routes connecting people to 139 trunk stations. Fare is charged only at entrance of the station regardless of travel distance or number of transfer within the system, and usage of solely feeder service is free. With a population of 7.8 million people, the BRT system serves a daily demand of 2.2 million passengers. The total fleet reaches 1697 and peak frequency reaches 320 buses per hour per direction on the busiest segment.

The TransMilenio system was expected a lot at its beginning to solve problems of slowness, inefficiency, inequity, contamination and safety (Sandoval and Hidalgo, 2004). It did show its efficiency especially during the first few years. A study in 2002 found a reduction of 79 percent in collisions, 43 percent in air pollutant emission SO_2 and 32 percent of average trip time (Sandoval et al., 2004). Given that the figures came from simple before-after comparison, the credits might not all go to the implementation of TransMilenio. But the general effects in travel time saving, air pollutant decrease, road safety improvement, land value increase, with a sustainable financial scheme were widely recognized using different methodology (Bocarejo and Oviedo H., 2012; Hidalgo, Pereira, Estupiñán and Jiménez, 2013). In early years, the satisfaction polls turned to a rating of 4.64 out of 5 and 98 percent of the users found it good or very good (Gilbert, 2008). The Bogota case has also been seen as a role model for sustainable transport solution in developing countries.

However, criticism has never stopped with the project, especially after the first few years. The largest criticism is regarding the capacity during peak hours. Stations are overcrowded with long queues. Such queues not only make vehicle crowded but also increase boarding time and cause delay (Cervero, 2005; Gilbert, 2008). Large crowd further brought risks for pick-pockets and robbery.

The second criticism is regarding price and equity. A public-owned company TransMilenio S.A. is in charge of infrastructure and management. All operational costs are covered by the private bidding operators without subsidy. Though a single fare is only 0.66$[6], it's 6 percent higher than the traditional bus system. The fare has kept increasing, making it unfavorable to the low-income groups. They use TransMilenio less than expected. While the rich people still use automobile due to the low service level of TransMilenio, middle-income group thus becomes the disproportionate largest user group (Kaufmann, 2012). This is partly due to the higher price, and partly due to the route plan, which is another issue widely criticized. The routes are not covering the lower income area, at least in the first stages of construction. So the system benefits middle class more but leaves the majority of the low-income population out (Gilbert, 2008). Low-income people usually live in the southern and western and are further away from job locations, so they have to travel longer distance and time (Bocarejo, Portilla and Pérez, 2013). Considering fare level and access to TransMilenio, people in low-income area have a generally lower accessibility to job at a much higher percentage of income spent on transportation (27 percent compared with 3 percent) (Bocarejo et al., 2012).

For the sake of financial sustainability, Bogota chose to set the fare to be cost recovery, which increased the burden of mobility to the low-income people. As a pilot solution, Bogota launched a pro-poor subsidy program with the assistance from World Bank in 2014.

The subsidy schema is designed as follows. The country has a national poverty targeting system and database (the Sistema Nacionalde Selección de Beneficiarios, SISBEN). Each individual is given a SISBEN score to be classified into one of 6 poverty levels within the system. Citizens that have a SISBEN score of 40 or less can apply a public transit subsidy for maximum 40 trips per month (on average this represents 50 percent discount for trunk services). The subsidy is targeted to benefit 900 thousand people but only 260 thousand have applied and 160 thousand have validated their cards until April 2015 and brings up the issue of targeting the people in need, which is a general question in demand side subsidy programs. This results in a subsidy amount of nearly 2.5 million US dollars (Rodriguez, Gallego, Marinez, Montoya and Peralta-Quiros, 2015).

[6] As a reference, the gross domestic product (GDP) at purchasing power parity (PPP) per capita in Colombia in 2016 was 13,910$ according to World Bank.

For those who take part in the program, the subsidy is quite helpful. The subsidy recipients are proved to increase monthly trips by nearly 56 percent. There's also a significant increase in transfer. Based on better transportation affordability, the subsidy program is considered to be helpful to the most vulnerable workers (Hernandez and Quiros, 2016) and decreased the benefit gap between different income groups (Guzmán, Oviedo, Rivera and Cardenas, 2016). An increase of 19 percent - 22 percent was estimated in the hourly wage of informal workers. The total transport expense didn't change significantly however. Experience from Bogota subsidy program highlights the complementarity between mobility and informal activity productivity. It aids the poor not only in reducing transport expenses but also through inducing higher income benefited from more trips. However, there's still problem of financial sustainability issue.

Though with relatively high fare in the users' eyes, Bogota has actually been proud of its financial scheme in BRT project that the public has no huge burden in operation subsidies but only needs to invest in infrastructure. During the first five years, most of the operators have profited while the public company made a loss. Some recognized the indirect subsidy in the process (Gilbert, 2008). Regarding the operation, the operators don't pay for the police and security equipment. They also pay less for the diesel from the State Petrol Company. Regarding the low-income users, they are benefited through longer travel distance paying the same fare as middle-class who live closer to the working place. They also benefit from the free feeder service since they are free and mainly serve poor neighborhood far from the stations.

3.4 Summary

The public transport policies in 3 cases differ so much, so do the city backgrounds. In table 2 the basic information of the cities as well as their subsidy policies are listed for simple comparison. As the initial purposes of the subsidies are different, judgement of which one is better is meaningless. However, there might still be some take-away recommendations.

First of all, there are different types of subsidies besides financial aid to balance budgets. Nash et al. (2002) distinguished between explicit and implicit subsidies and further classified for both of them. Explicit subsidies include operation subsidy as well as user subsidy. Implicit subsidies include underpriced or even free provision of infrastructure, failure to internalize externalities and foregone tax revenues. It's important to distinguish between operation and user subsidy.

There's also a trend to favor user subsidy (Ison and Rye, 2008). It's also important to recognize the implicit subsidies which are often neglected.

Table 2: Comparison of London, Beijing and Bogota

	London	Beijing	Bogota
Area (km2)	1,572	1,368	1,587
Population (million)	8.5	18.8	8.1
Car ownership	0.3 per adult	0.49 per household	0.2 per capita
PT mode share	44 percent	39 percent	57 percent
Transport expense	14 percent of total expense	10 percent of total expense	3 percent-27 percent of total income
Public responsibility	Planning, management, infrastructure, fare level	Almost all	Planning, management, infrastructure
Private responsibility	Operation through contracts (regarding buses)	Infrastructure and operation (regarding 3 metro lines under PPP)	Operation through contracts, fare collection through another contract
Subsidy scheme	Regulated by quality incentive contracts; distinguishing (non)profitable routes; 30 percent of total costs	Negotiation between authority and operators; block grant to cover all deficit	Poor-targeted subsidy to increase mobility
Other transport policy	Congestion pricing	Driving restriction; vehicle registration restriction	Pico y Placa program (Vehicle usage restriction in peak hours); car-free day

Source: World Bank, Beijing Year Book 2017

Secondly, the objective of each subsidy expense should be clear. For example, whether it's to sustain the basic service in remote area, to encourage mode shifts from automobile users to reduce congestion, or to aid specific groups out of social exclusiveness. This requires distinguishing between profitable and unprofitable routes, peak hour and off-peak hour. Public subsidy could be avoided through internal cross-subsidy.

Moreover, subsidy policy is only part of a larger public policies. On the one hand, deregulation or not and how to do it are bigger questions to answer before how to subsidize. On the other hand, subsidy is only second-best pricing and first-best pricing should always be an alternative in consideration. Experiences also show that a successful scheme to encourage usage of public transport always needs to restrain the use of automobile (Mallard and Glasiter, 2008).

Lastly, the effects of public intervene is always comprehensive. It’s necessary to include all second order effects but it’s also important to balance which are more urgent. For example, no operation subsidy leads to a higher fare level in Bogota and sacrifice the low-income, but financial sustainability is a bigger issue for the government at the beginning.

4 Background of AV

Trials with autonomous vehicles, in a broader sense, started not long after the motorcar. It was seen as the first "driverless" car when Francis Houdina controlled a car with radio technology sitting in a vehicle behind the driverless car and followed it through streets in Manhattan. There has been an ongoing passion about autonomous vehicles after this first trial. The cover picture shows an advertisement from December 1956 for an electronically controlled driverless car. The modern era enthusiasm for autonomous vehicles started in the early 2000s, when the military department of the United States held its Grand Challenge to build autonomous vehicles with $1 million prize. Unfortunately, no team completed the mission to navigate 142 miles at that time. Important breakthroughs came after Google started its autonomous vehicle project Waymo in 2009. Major automobile manufacturers (BMW, General Motor, Ford, etc.) as well as huge technology enterprises (NVDIA, Uber, Baidu, etc.), joined in one after another in recent years. With Waymo announcing its plan to start autonomous taxi business later this year, leading AV developer is about to commercialize its technologies.

4.1 Level of Driving Automation

The fully autonomous vehicle is yet to come in the near future, but important progress has been made towards the final goal. To clarify the different technology stages, SEA International published a classification system in 2004 and revised it in 2016, which is now widely recognized to classify the automated driving system technically. The classification is based on the roles of automated driving system (ADS) in the driving processes. An important concept is dynamic driving task (DDT), which includes all real-time operational and tactical functions required to operate a vehicle in on-road traffic (SAE International, 2016). Among other features, it incorporates lateral and longitudinal vehicle motion control, object and event detection and response (OEDR). While a level 1 autonomous vehicle is able to assist human driver to partially control vehicle motion, for example parking assistance or adaptive cruise control (ACC), level 2 could be seen as a combination of all level 1 functions to realize driving automation partially instead of just driving assistance. Technologies to this step are already mature in market.

Level 3 realizes the entire DDT by involving OEDR, which means the system can be fully automatic in certain conditions, but a human driver must be ready to take over the duty whenever there is a system failure or the conditions are no longer satisfied. A current example in market is the Audi's AI Traffic Jam Pilot system equipped in its new A8's vehicle product. The system can be activated under traffic jam or slow highway traffic with speed lower than 60 km/h. While activated, the system will check the human driver's status through a camera and make sure that he/she is always ready to take over the driving task. However, the technology is somewhat unfavored by other developers. In March 2018, Uber's autonomous vehicle caused the first fatal accident in history[7]. The system didn't execute braking in response to a pedestrian, and the driver wasn't focused enough to step in either. Level 3 is seen as an intermediate technology but not suited for market introduction since it still requires human attention all the time. Uber's tragedy further confirmed other developers' plans to skip level 3 and directly invest in level 4 vehicles.

Level 4 vehicles don't need human drivers to stand by, which enhances the security level a lot. But the system still needs to be switched on and off manually at starting and destination points. Waymo's testing vehicle is typical for level 4 technology. Level 5 further realizes fully automation through an automated start of the system so the vehicle can drive itself from the parking lot to pick you up directly in front of your working place, i.e., no human needed in vehicles.

In this thesis, the discussion is under the scenario of level 5 if not further specified, which is expected to be introduced between 2025-2045. A lot of benefits rely on the wide adoption of the technology. To simplify, it is assumed that such level 5 AVs are fully adopted in the discussion. From previous experience, it will take one to three decades for autonomous vehicles to dominate the sales market and a further one to two more decades to be widely adopted for road travelling. Without policies restricting human driving and conventional vehicle sales, it is expected that the scenario discussed above would come around 2100 (Litman, 2018).

[7] http://www.bbc.com/news/world-us-canada-43497364

4.2 New mobility concepts

Based on the realization of fully autonomous vehicles, shared mobility solutions become more attractive than they are today, which could reduce vehicle ownership and even total vehicle distance.

A private autonomous vehicle (PAV) could be better shared by household members than conventional private vehicles. For example, a working member rides an autonomous vehicle to its working place. The vehicle could then go back home to serve other members such as taking kids to school. While in the traditional scenarios, a second private vehicle is needed. PAVs offer more possibilities to coordinate household members' schedules with only one vehicle.

A second type of shared mobility is the shared autonomous vehicle (SAV) service. An SAV is also called a self-driving taxi, which explains how it works. In this case, people only pay for the mobility service, which is more affordable than a PAV. It is also more cost-efficient for those vehicle owners with low mileage. However, some degree of convenience is sacrificed in exchange. The first inconvenience comes from the response time of SAV, making the service less instantly than a PAV. When the shared fleet size is not big enough, people might need to wait for a while to get an available vehicle in a high-demand scenario (Bischoff and Maciejewski, 2016; Boesch, Ciari and Axhausen, 2016). The second inconvenience is the privacy that SAV users have to give up. The travel data is naturally recorded for operational reasons, but it still remains unclear who owns the data and who can access it. Should the data be anonymous or aggregated to protect individual's personal information? Furthermore, for the convenience of investigating vehicle damages, should there be an in-vehicle video recording? The privacy issue is important in legislation and regulatory of SAV business and requires further research (Fagnant and Kockelman, 2015; Litman, 2018). Lastly, people might view vehicles as more than a mobility tool. For some people it is an important relaxing space itself and therefore comfort is extremely important. It could be a temporary storage space and people might want to leave their personal belongings in it for a short period, e.g., gym bags. Vehicle ownership is also a symbol for the social state that some people might not want to give it up. All these drawbacks will not make SAVs a perfect substitute for PAVs, especially for those who put high-value in the non-utilitarian motive on mobility (Krueger, Rashidi and Rose, 2016). This preference for PAVs over SAVs is confirmed by Haboucha, Ishaq and Shiftan (2017) through a stated preference questionnaire. They found out that 25 percent of the respondents won't be willing to use SAVs even when the price is set to 0. Further policies restraining private ownership or private vehicle usage will be needed if a world without private vehicle ownership is expected.

Another shared mobility solution is dynamic ride sharing (DRS) with AVs. DRS would further reduce the cost of travel compared with SAVs, but feature longer travel times (Fagnant and Kockelman, 2018). Besides users' costs, DRS is also expected to largely reduce overall vehicle distance travelled and thereby reduce the externality in automobile usage. But similarly, more privacy and comfort, even security to some degree, have to be sacrificed compared with SAVs. Although DRS might be seen as a further shared economy solution based on SAVs, they are actually perceived to be two totally different modes from users' eyes and should be investigated separately (Krueger et al., 2016).

Connected autonomous vehicles (CAV) is another concept to mention here. A CAV is an autonomous vehicle equipped with communicating technologies to further improve performance, including communication with humans, other vehicles (V2V) and infrastructure systems (V2I). It's more like an additional function rather than a new mode that has the potential to radically reform the future mobility scenario, but it would be critical to realize some of the benefits. An application of CAV-driving could be vehicle platooning, generally defined as a collection of vehicles that travel together, in actively coordinated formations (Bergenhem, Pettersson and Coelingh, 2012). A leading vehicle is in the front and other vehicles follow in close distance and small headway, which could improve traffic flow performance significantly. Different projects on platooning are under research in the world and they differ only in detail. Some are only applicable to dedicated lanes, others could be applied to mixed traffic. Some only support coordination of the same type of vehicles, i.e., car or truck, others could support the mixture of both types in the system. It is assumed that level 5 AVs being discussed here are equipped with communication technologies and able to perform platooning.

5 Impacts of AV

5.1 Potential benefits

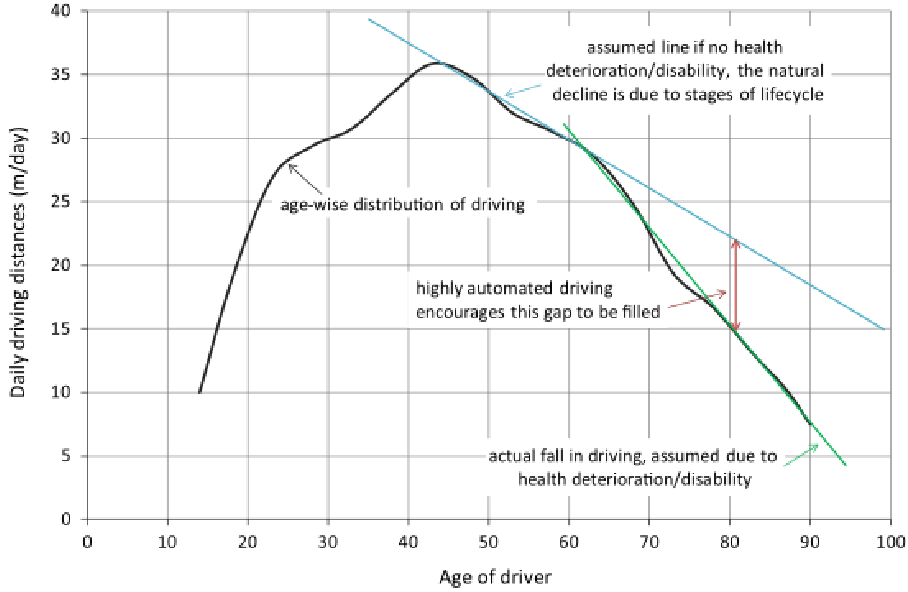
5.1.1 Mobility for certain groups

One of the original intention of AVs is to help those people who can't drive, namely the disabled, elderly, children and adults who don't own a driving license. Enhanced mobility for them brings further positive externalities such as more job opportunities, less isolation and higher quality of life (Lutin, Kornhauser and Lerner-Lam, 2013). Mobility for elderly people is especially important as the world is in an accelerated process of population aging. According to United Nations (2015), the share of older people (age of 60 or above) is expected to be over 25 percent in Europe and North America by 2030.

Generally speaking, senior people are found to travel less frequently as well as shorter distances, but their travel demand is showing an increasing tendency (van den Berg, Arentze and Timmermans, 2011). Senior people also prefer automobile to public transport or walking/cycling more compared with younger people, but especially in higher ages many are not able to drive a car anymore. They have to either switch to less favorite alternatives and likely suffer a sense of loss, or persist in driving and increase the risk of accidents for all road users (Alsnih and Hensher, 2003). These forces work together towards a society with more aged drivers in the future, and these aged drivers are very mobile and highly automobile dependent (van den Berg et al., 2011). For those insisting to drive, autonomous vehicles offer safer and faster trips. For those turning to other alternatives, autonomous vehicles offer a better substitution to satisfy their demand. Some researchers tried to quantify the travel demand increase generated by the second effect.

Wadud, MacKenzie and Leiby (2016) investigated travel data from the US Federal Highway Administration (NHWA) and mapped the demand distribution of age. The travel demand peaks at 44 and then experiences two decline stages. They assume that the decline between 44 and 62 is the natural decline of activities with growing age while the drop after 62 reflects the shift to other modes due to insufficient driving ability because of health issues. The gap between the interpolated natural decline and the actual decline becomes the new demand for elderly people generated by autonomous vehicles (Figure 9). They estimated a 2-10 percent increase in overall travel demand by car. However, this is an estimate on the high side according to the authors.

Figure 9: Change of travel demand in automobile with age



Source: Wadud et al., 2016

For disabled groups, aside from investments in disabled friendly transit infrastructure, a large number of public transport budgets are still used to provide on-demand service which could be very costly (Anderson, Kalra, Stanley, Sorensen, Samaras and Oluwatola, 2016). Since the cost is usually covered by taxpayers, SAVs could substitute these on-demand services at a much lower cost and improve social welfare.

5.1.2 Road safety

Although there are already several cases of traffic accidents, even fatal ones because of autonomous vehicle, the fully automated vehicle is expected to largely reduce traffic collision. Since 90 percent of the accidents in the U.S., as well as over 40 percent of the fatal crashes among them (NHTSA, 2008), are related with human errors including speeding, drunk or tired driving, or use of mobile phone, it is likely that AVs will possibly reduce collision rate. Optimists believe that the fatality rate could eventually be similar to that in aviation and rail, which is about 1 percent of the current rate (Hayes, 2011). Other estimation on collision/fatality reduction by autonomous vehicle is in relatively smaller scale. People concern about the other effects that involve new risks from new technologies.

The most important reason for reduced traffic collision is that AVs could avoid errors from human drivers. However, AVs could also bring the risk of system failures. For example, a system won't be distracted because of talking on the phone, but it is possible that one of the sensors is not working properly, which brings a similar risk of accident as a distracted human driver (Kockelman, Boyles, Stone, Fagnant, Patel, Levin, Sharon, Simoni et al., 2016). With more developed technology and knowledge it is possible to lower system failure rates compared to current values, but it is not likely to ever have no failures at all. The second effect is risk compensation. When technology guarantees a safer driving environment, people tend to behave riskier. Such inclination applies to both in-vehicle passengers and pedestrians (Millard-Ball, 2018). The third thing to notice is that the transition to AVs takes time. When conventional vehicles and AVs are mixed on the road, conventional human drivers may lose some information from previous human contact and undertake riskier moves (Sivak and Schoettle, 2015), such as cooperative driving during lane changing. V2V technology may solve the problem in the end, but vehicle to human communication could be problematic during the transition period. Lastly, AVs' benefits will induce higher usage of automobiles. The accident rate could drop substantially, while the absolute number of accidents might not necessarily with a larger base (Litman, 2018).

Nonetheless, effects of these concerns are small compared with the improvement because of avoidance from the human driver errors. It is widely recognized that AVs will be much safer than human drivers (Fagnant and Kockelman, 2015; Kockelman et al., 2016; Litman, 2018). The data of 90 percent accidents induced by human according to NHTSA is often cited. Some believe that this part of collision could be almost fully eliminated with autonomous vehicles. However, the real impact should be relatively smaller.

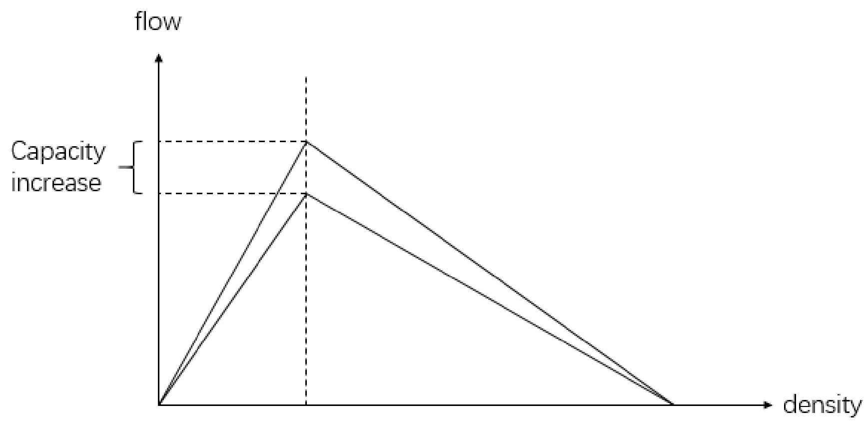
Further issues regarding road safety might involve ethic and liability concerns. Such as who are responsible for what kind of potential accident? Owner of the vehicle, operator of the SAV service or manufacturer of the vehicle? These questions are less relevant for the thesis and won't be discussed here.

5.1.3 Road capacity and congestion

Road capacity and congestion level could be improved through several ways, including higher speeds, shorter reaction times, smaller vehicles, cooperative driving, more stable flows, better route choices and fewer accidents.

Without limits of human attention for road safety, the speed restriction on highways could be relaxed. Things will be similar to the current German situation where there is no general highest speed limits but people would not drive as fast as the vehicle engine could let them. According to data in Brandenburg, average driving speed is 117 km/h when the speed is restricted at 120 km/h and 127 km/h when restricted at 130 km/h. It further increases to 137 km/h without speed restriction, both statistics are calculated from 4-lane highways (Scholz, Schmallowsky and Wauer, 2007). There are lots of reasons stopping people from driving even faster. Wadud et al. (2016) started from the fact that higher speed costs more fuel (detailed discussion see 5.1.4). They assumed that AVs will increase their speed until the marginal value of time saved just matches the marginal cost of increased fuel consumption. The idea is applied to the U.S. scenario and the equilibrium speed for AVs in the U.S. will increase to around 140km/h, somewhere just close to the current German value. Looser speed limits or even no speed limits lead to a higher free-flow speed and increase capacity as illustrated by Figure 10. Taking free-flow speed as the speed limit, an increase from 120 lm/h to 140 km/h theoretically leads to a 16.7 percent increase in capacity.

Figure 10: Road capacity increase in AV system by looser speed limit



Note that this effect is stronger for highways but weaker for urban roads, because there are intersections/traffic lights in urban road networks. Intersections are the bottlenecks to constrain the network capacity. On the contrary, AVs might make turns slowlier than conventional vehicles at intersections as a sacrifice for riding comfort as shown in the study of Le Vine, Zolfaghari and Polak (2015). According to their theory, there is a higher requirement for comfort since people would expect to utilise in-vehicle travel time more productively. Speed, acceleration/deceleration and steering angle have to be controled in order to ensure a comfort level comparable to current rail-based transits. Such comfort level is said to be the minimal requirement if passengers expect to work in the vehicle. It is estimated that an adoption rate of 25 percent of AVs will bring an increase of average delay of 5 to 36 percent at intersections. However, this study does not consider other benefits brought by AVs, which makes the scale of capacity loss questionable.

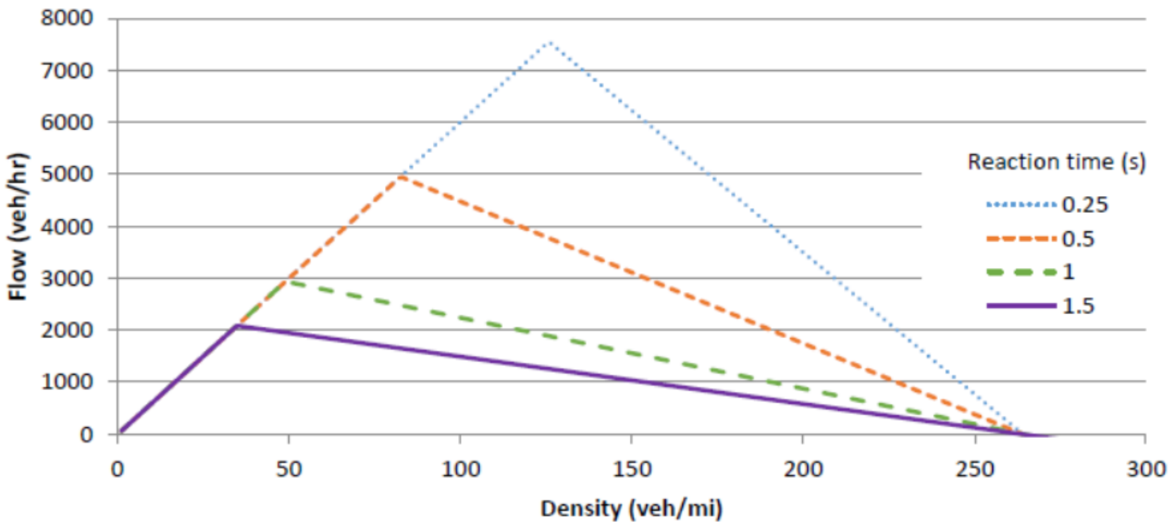
The second source of capacity increase comes from a shorter reaction time. A shorter reaction time allows shorter spacing under same speed and hence increase capacity. Levin and Boyles (2016) tried to compute the critical density considering reaction time to derive capacity. Critical density is the largest density possible to keep free-flow speeds. In this case, the following distance equals reaction time multiplying free-flow speed. Given the distance, critical density and capacity could be derived using following equation:

$$\mathrm{Q} = \mathrm{V} * \mathrm{k} = \mathrm{V} * \frac{1}{V\Delta t + l} \quad 5$$

(Q: capacity; V: free-flow speed; k: saturation density; Δt: reaction time; l: vehicle length)

Other variables kept constant, capacity increases monotonously with shorter reaction times by increasing the second part. The authors assumed the reaction time of a human for levels from 1 to 1.5 seconds. Thus, a shorter reaction time of 0.5 seconds could increase capacity remarkably (Figure 11).

Figure 11: Road capacity increase in AV system by shorter reaction time



Source: Levin et al., 2016

In the urban scenarios, a shorter reaction time increases intersection capacity through quicker start ups at traffic lights (Fagnant and Kockelman, 2015; Hars, 2016). On the one hand, vehicle-to-infrastructure technology informs the AV precisely when the light turns green. On the other hand, system operation excludes those new drivers, senior drivers, or distracted drivers who might take more seconds to start up.

A similar effect of capacity increase results from smaller vehicles (smaller *l* in Equation 5) that could be derived by the same equation. Vehicles are expected to be generally smaller because of two effects. First, a lower risk of accident would allow smaller vehicles to keep the same safety level (Wadud et al., 2016). Second, SAV operators tend to offer vehicles whose sizes are adapted to the occupancy to be cost efficient (Ross and Guhathakurta, 2017), while PAVs for households are often not fully occupied. Users of car sharing today also tend to drive smaller vehicles than private vehicle owners (Chen, Kockelman and Hanna, 2016). Assuming that SAVs would gain its popularity in the future, it could be expected that vehicles on road would be generally smaller.

Traffic flows could be more stable through better information about vehicles in the front. Stable flow could reduce delay and congestion. This could be expected pretty soon since it mainly benefits from level 1 or 2 automation technologies. Kesting, Treiber and Helbing (2009) extended a car following model (IDM) to feature the behavior of vehicles equipped with ACC. ACC vehicles realize smoother deceleration than human drivers especially when small perturbation happens, e.g., lane changing. Only accounting for this effect, they observed a sensitivity of 0.3 in the simulation, i.e., every percent more vehicles equipped with ACC will lead to an increase of 0.3 percent in capacity. Another study that estimates effects of ACC calculates a 8 to13 percent increase of capacity in highways (Fagnant and Kockelman, 2015). However, there are also studies that reported different results. Shladover, Su and Lu (2012) used a microscopic traffic simulation program, Aimsun, to simulate the microscopic behaviors of vehicles equipped with ACC and cooperative ACC (CACC). They used data gathered from current ACC users to calibrate the parameters for the car following model. Hence, their model is claimed to be more realistic than the earlier mentioned IDM model from Kesting et al. (2009). They didn’t find a significant increase in lane capacity by the adoption of ACC. However, they proved the effects of smoother deceleration to increase capacity through adoption of CACC. CACC vehicles receive more information from surrounding vehicles that they make better decisions. The effect is nearly quadratic because a CACC vehicle can only perform cooperatively when it is following another CACC vehicle. The capacity increase is smaller for low adoption rates but significant with higher adoption rate. With 100 percent vehicles equipped with CACC, the lane capacity could be nearly doubled.

A similar effect to stabilize traffic flow was obtained by an experiment in Arizona (Stern, Cui, Delle Monache, Bhadani, Bunting, Churchill, Hamilton, Haulcy et al., 2018). They replicated the phantom traffic jam experiment introducing vehicles with autonomous velocity control. When perturbation happens in front of the AV, the system could estimate the average velocity of the vehicle in the front. It could then derive an optimal velocity to stabilize the flow. Their result showed that only one AV versus 20 human controlled vehicles could dampen such stop-and-go waves. It shows that such improvements in flow stability could be realized not only with low levels of automation, but also with low levels of adoption rates (less than 5 percent).

Furthermore, NHTSA estimates a 25 percent of congestion attributable to traffic incidents (Fagnant and Kockelman, 2015). Thus, improvements in road safety would also reduce congestion in a way.

To sum up, several researchers estimated or assumed the average capacity increase brought by autonomous vehicles and it varies depending on the level of automation, adoption rate and usage of SAV/DRS. Highway and urban road need to be distinguished regarding capacity increase effect. For highways, estimations of overall capacity increases could be between 80 to 370 percent, and for urban roads, 40 to 80 percent (J. Meyer, Becker, Bösch and Axhausen, 2017). Even though road capacity could be largely increased, travel demand is also increasing undoubtedly. Whether congestion could be reduced remains unclear.

5.1.4 Environmental impacts

Autonomous vehicles can bring positive environmental impacts in energy saving and emission reduction. The ASIF framework (Schipper, 2002) is widely used in emission research in transportation. The name of the framework comes from the first letter of the four factors influencing the emission level:

$$\text{Emission} = \text{Activity level} * \text{Mode share} * \text{Energy intensity} * \text{Fuel type} \qquad 6$$

Activity level represents total travel demand and its product with mode share reflects travel demand by car. It's likely that travel demand by car will increase in an AV-system. Details will be discussed in 5.2.. Energy intensity reflects the vehicle's feature and is measured in fuel per passenger kilometer. Reduced energy intensity is the key improvement to reduce energy consumption. Fuel type is a feature of the fuel and transforms the result from energy consumption to emission in the equation. In this analysis, fuel type is assumed to be unchanged. Thus, the key topic of this section is how AVs reduce the energy intensity compared with conventional vehicles.

Firstly, AV technology can reduce energy intensity by smooth acceleration and deceleration. Currently, solely with adaptive cruise control, some EU cities witnessed fuel savings of 5 percent (Chen, Ardila-Gomez and Frame, 2017). Secondly, fuel consumption could be saved with more stable traffic flow. Traffic flow could be more stable with autonomous vehicles through several effects mentioned in 5.1.3. In the experiment which repeated phantom traffic jam by Stern et al. (2018), a reduction of 42.5 percent in fuel consumption among the whole fleet was observed. Thirdly, when the collision rate is largely reduced, vehicles could be made much lighter and thus reduce the energy intensity (Anderson et al., 2016; Hars, 2016; Wadud et al., 2016). What's more, Fagnant, Kockelman and Bansal (2015) mentioned fuel saving with SAV through fewer cold starts. A shared vehicle will travel frequently through the day than a conventional private car so there will be fewer cold starts in total. Cold starts emissions are much higher than in a warmed-up situation. High usage of SAV could thus reduce the average energy intensity.

However, as mentioned earlier, AVs could drive at a generally higher speed especially on highways, which would increase energy intensity (Brown, Gonder and Repac, 2014).

Considering the increase in travel demand, net effect of energy consumption is not apparent to tell. Some researchers tried to quantify the net effect. Wadud et al. (2016) used the ASIF framework and estimated the magnitude of the effects in each component under 4 different scenarios. The results varied a lot from reduction of 45 percent to increase of nearly 100 percent. However, it is highly unlikely in the authors' eyes for the worst situation to happen. Brown et al. (2014) estimated a change with larger range, from a 90 percent reduction to a 150 percent increase.

5.1.5 Parking

Parking space could be saved especially in city centers where the land value is high and parking space is sparse. Saving parking spaces could deliver further benefits such as better walkability, higher-quality open space or better urban vitality. Both the number for parking slots as well as size for single parking slot could be reduced with AVs.

Total number for parking slots could be decreased due to three mechanisms. The first is that AVs can self-park in a more remote but cheaper place other than the neighborhood at the destination. Parking space in dense areas could be saved for other purposes. The vehicle could even park back home if fuel costs less than parking, which is likely for commuting into city center with expensive parking (Fagnant and Kockelman, 2015). Total parking spaces could then be decreased while the total number of vehicles need not be. The second is through a wide adoption of SAVs, which reduces the total number of vehicles. Ideally, when the fleet of SAVs is large enough, all travel demand could be satisfied within a short response time and PAVs could be eliminated. Such substitution effect is mainly dependent on the max waiting time allowed. Boesch et al. (2016) found the substitution effect to be non-linear and there's a scale-effect in it. In the Zurich scenario on which they did a simulation, an SAV could replace 4 or 10 private cars when the maximum waiting time is accordingly 5 min and 10 min. Similar results were reported for 1:11, 1:8, 1:5 etc. (Burns, Jordan and Scarborough, 2013; Fagnant, Kockelman et al., 2015). The third mechanism is the fact that an SAV uses on average fewer parking slots. A conventional vehicle is typically parked 23 hours per day and uses several parking spaces regularly (Litman, 2006), while an SAV will spend much longer time in ride or cruising and could use as few as one parking slot only in non-peak hour. The parking demand per SAV is also decreased as the fleet size increases, similar to the effect in response times (W. Zhang, Guhathakurta, Fang and Zhang, 2015).

The dimension for a one-car parking slot could be smaller in a fully automatic world. On the one hand, vehicles could be made smaller as analyzed in 5.1.3. On the other hand, no additional space is needed for passengers to get in and out easily, since people will be already dropped off before parking with level 5 automation (W. Zhang et al., 2015).

5.2 Travel demand

With AVs, especially with fully automated technology, travel demand in car usage will possibly increase. The increase of demand is induced by the benefits of AVs, but will counteract the benefits in return. For example, less congestion attracts more car usage, while increased car usage could bring congestion back. The interaction makes the direction of net effects difficult to determine.

In the short term, travel demand may be affected through mode shifts, especially from public transport to automobile. While in the long run, more fundamental changes could be generated and increase travel demand in return, such as residential location choice. People might live farther from city center and commute longer distance because car travel is faster (Bansal, Kockelman and Singh, 2016; Millard-Ball, 2018; Wadud et al., 2016). Urban structure could be reshaped after a long period.

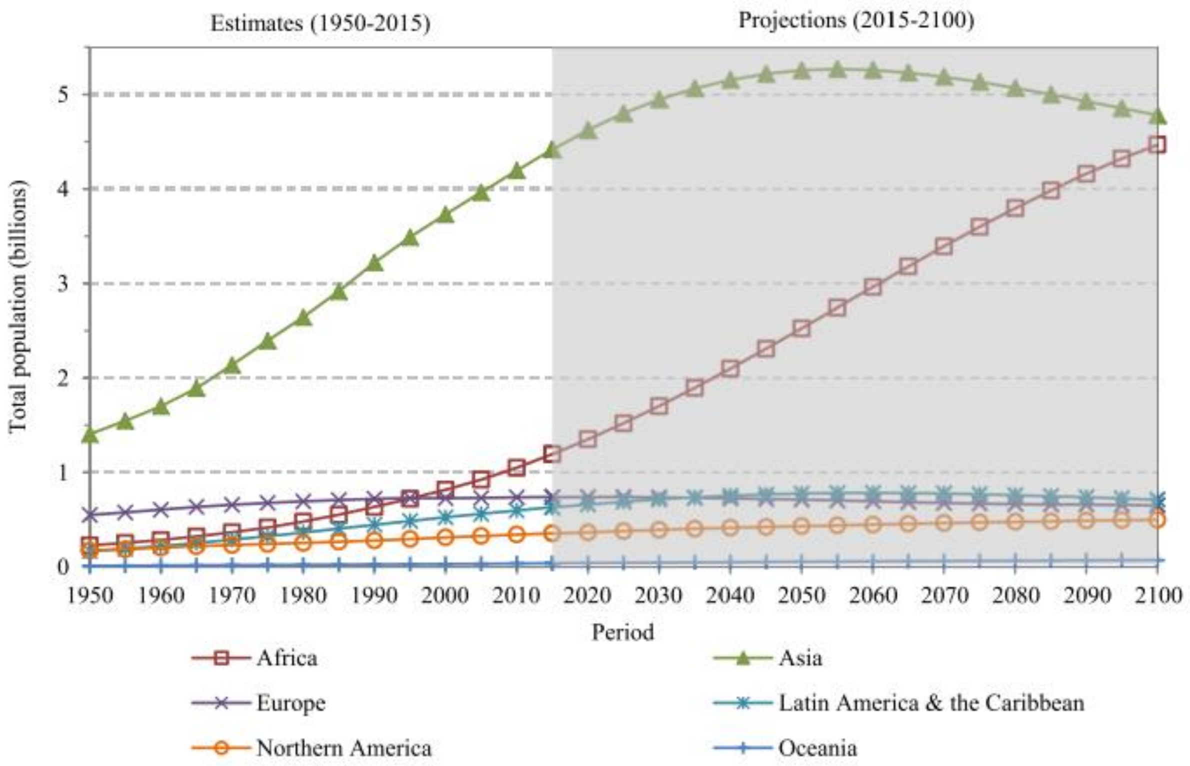
Another substantial increase may come from empty rides. With PAVs, empty rides could be generated for parking, pick-up of goods, or repositioning when family members share one vehicle. Meyer et al. (2017) estimated a 53 percent increase in the Switzerland scenario for PAV empty rides. The operation of SAVs will also generate empty rides during cruising, relocating and pick-up. Fagnant et al. (2015) simulated in MATSim using the city center area of Texas and the result showed an 8 percent increase of empty rides. Burns et al. (2013) reported a lower number of empty rides with only 0.1 vehicle miles per trip. Given that an average trip per vehicle is estimated to be 5.8 miles, this indicates an increase of less than 2 percent. Both two researchers concluded that empty rides will drop as demand intensity or the fleet size of SAVs increases.

A third demand increase could be resulted from a decrease in generalized costs, including shorter travel times or smaller value of times (VOT). Meyer et al. (2017) studied the induced demand because of higher accessibility in the Switzerland scenario with SAVs. The estimation is simplified such that accessibility only considers travel times. Only a 0.1 percent increase is observed and mainly in rural municipalities. After including other demand increases, the net accessibility in the country is still increased by 1.4 percent weighted by population size. Gucwa (2014) estimated the induced demand because of a road capacity increase as well as diminished VOT. VOT could be lower because AV users are free from driving task and can utilize in-vehicle time more productively. The scenario in the study is urban travel in San Francisco Bay Area excluding car sharing. When VOT drops to be the same as high quality rail and road capacity is increased by 10 percent, vehicle miles traveled would increase by 4 percent. When VOT drops even lower to be half of the current level and capacity is doubled, vehicle miles traveled would increase by 7.9 percent.

Another thing to notice is the population increase before wide adoption of fully autonomous vehicles, which could be a large source of total demand increase. United Nations (2017) estimate the world population to be 9.8 billion in 2050 and 11.2 billion in 2100, while in 2015 there are only 7.4 billion. Suppose urban road capacity in 2100 gets to be increased by 50 percent because of autonomous vehicle technologies, such capacity increase has to deal with demand increase resulted from a 50 percent population increase.

It might be more of a problem in developing than in developed countries since population growth mainly happens in Africa and Asia (Figure 12). At the same time, developing countries are also where urbanization and motorization are going to happen in the future decades. In newly industrialized countries such as China, Brazil or Mexico, mega-cities are emerging and facing extreme congestion problem. Take Beijing as an example, where streets are already much congested in peak hours, increased capacity brought by autonomous vehicle is highly probable to be offset by increased population. Congestion could probably be even more severe if no other policies are accompanied. In least developed countries such as most sub-Saharan countries, where most of the population increase takes place, capacity increase from autonomous vehicles would hardly be sufficient to serve the population. Capacity needs to be increased also from infrastructure side, such as building highways for inter-city traffic or increasing lanes for intra-city traffic. Infrastructure in these countries are not yet complete, which offers much potential for capacity increase. On the contrary, it wouldn't solve congestion problem by adding lanes in cities like Beijing. While building infrastructure costs a lot, these poor countries might not be able to cover the cost alone. Population increase and urbanization are not accompanied with fast economic growth in most sub-Saharan countries (United Nations, 2017). While there are lots of huge metropolitans arising in the urbanization process of newly industrialized countries, urbanization in the poorest African countries is believed to spread out in smaller secondary cities, where economy growth is even more slowly (Cohen, 2006). Poverty could be a big obstacle for them to construct the necessary transport infrastructure.

Figure 12: World population growth projection 2015-2100



Source: United Nations, 2017

5.3 Travel costs

The development of technology has always made travelling less and less costly, in the sense of generalized cost. Generalized cost is an important concept to model travel behavior. It is a weighted sum of all the main attributes related to the disutility of a journey, including mainly time spent and all monetary expenditures (Ortuzar and Willumsen, 2011). The coefficient for each attribute reflects the traveler's subjective perception regarding risk, comfort, etc.

$$C = \sum a_i t_i + \sum a_j f_j + e \quad (7)$$

(a_i: VOT in travel time of type i; t_i: travel time of type i; a_j: weight for monetary charge of type j; f_j: monetary charge of type j; e: other non-monetary disutility not included)

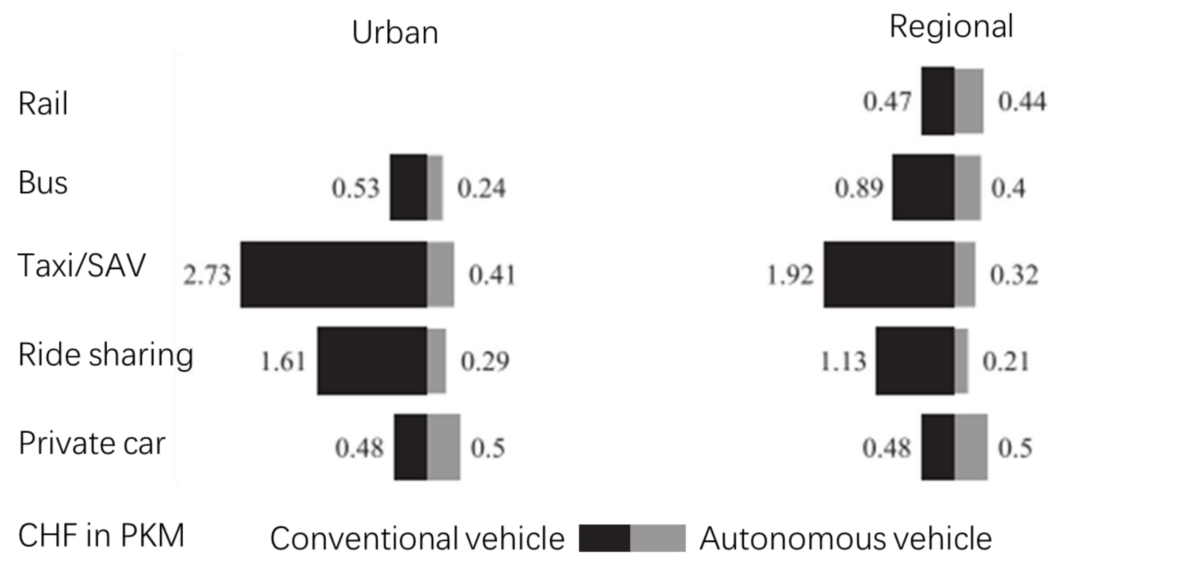
The first part of the equation measures the time cost of travel. With autonomous vehicles, the in-vehicle travel time could be shortened with better routing, higher speed and less congestion. When drivers are free from vehicle operations and able to perform other tasks, value of in-vehicle travel time is reduced by up to 31 percent of the current level (Steck, Kolarova, Bahamonde-Birke, Trommer and Lenz, 2018). Access and egress travel time could be much shortened because of door-to-door service. Vehicles could drop passengers off right in front of the door at destination and then park itself in the parking lot. Time for searching parking space is totally gone. But there could be a new waiting time, which might be high for SAV users in peak hour.

Monetary costs include fixed costs and variable costs. Fixed costs of a PAV might be unaffordable to the majority in the first stage of introduction. Typical as any other new traffic mode (train, airplane, automobile), packages of additional functions to realize automated driving (such as sensors, wireless networks, etc.) could generate more than ten thousand of extra dollars in vehicle manufacture cost. So they will be first applied to luxury cars for high-income groups (Juliussen and Carlson, 2014; Litman, 2018). But a lot of manufacturers have claimed that the price will drop quickly because of rapidly improved technology and larger production scale. For example, AV manufacturer Delphi plans to cut the extra cost of automated packages by 90 percent to only $5,000 by 2025[8]. The tendency of price decrease in the future is widely

[8] Reuters, https://www.reuters.com/article/us-autos-delphi/self-driving-costs-could-drop-90-percent-by-2025-delphi-ceo-says-idUSKBN1DY2AC

acknowledged and it is assumed that there is an annual relative decrease ranging from 1 to 10 percent. So it might take one to three decades until AVs are widely applied in all models in vehicle markets instead of only luxury models (Litman, 2018), although the price will still be 10 to 20 percent higher than for conventional cars of similar performance. The insurance cost for AVs are believed to be much lower than conventional cars because of improved safety performance, widely estimated parameters are about half of the current level (Bösch, Becker, Becker and Axhausen, 2017). For SAV users, fixed cost could be almost gone except for a possible member fee. But such member fee should be much smaller compared with the cost to own a private vehicle.

Figure 13: Estimated monetary costs of mobility in AV-systems



Source: Adapted from (Bösch et al., 2017)

Instead of fixed costs, substantially reduced variable costs might play a larger role to change the generalized cost of travel and then affect travel behavior. PAV costs less money per passenger kilometer than current conventional private cars. AVs' higher energy efficiency reduces expenses for fuel. Self-parking ability enables choice of cheaper parking place. SAV, which is also called self-driving taxi, would also be charged at a lower rate than current taxi service. In current taxi service charging system, labor cost constitutes a large portion. In Swiss scenario, 88 percent of the charges are used to pay the drivers' salaries (Meyer et al., 2017).

Charging for SAV could be much lowered since no driver needs to be paid anymore. SAV with ride sharing could further reduce the variable monetary cost.

Another thing to notice is that, with public transport also undergoing automation reform, cost for public transport also could be decrease sufficiently (Figure 13).

5.4 Summary

Just like any other new technology in the history of transportation, autonomous vehicles reduce the generalized cost of travel and make a change to people's travel behavior.

AVs reduce the time cost in travel through both reduced value-of-time, probably to the same level as the in-vehicle time of today's public transport. But the total time spent by autonomous vehicles could be much lowered than public transport under many cases. AVs offer door-to-door service and eliminate access and egress time to and from the parking space. Self-parking function further avoids the time spent to search for parking space. Increased capacity and reduced congestion decrease the in-vehicle time needed. The only increase might be the waiting time for the vehicles to pick up. But it could be controlled for SAV users if there's a fleet with a sufficient size and an efficient vehicle allocation system.

AVs reduce the monetary costs to travel especially for SAV and DRS users. Fuels could be saved and parking fees could be avoided. Additional cleaning fees could be applied as a new expense but are minor compared with the saving from human drivers ' income. For PAV users, saving in fuel and parking also apply. Vehicle acquisition could be more expensive especially during the first stage of introduction. But it could be expected to be more affordable in later years. Besides, insurance expenses are expected the be reduced because of better safety performance. However, whenever the generalized costs get to be decreased, further demand could be reduced. Travel demand increase firstly comes from the inevitable population growth, especially in cities of developing countries. Secondly, reduced generalized costs in car usage could attract users from other modes such as public transport or cycling. Especially the former captive riders could contribute a lot to vehicle usage increase. Lastly, reduced costs might encourage people to live farther from working place and commute longer distance, so that average vehicle distance traveled for single person might be increased. Besides costs and demands, autonomous vehicles have some externalities that have less things to do with travel behavior directly, including less emission, save of total parking space for more valuable usages, etc. However, these positive externalities rely a lot on the optimal increase in total demand. They could be largely offset when demand increases too much. It might happen when shared mobility is not attracting enough private vehicle owners.

6 AVs and PT subsidy

6.1 Necessity of public transport in AV-systems

Given the higher speeds, lower monetary costs as well as door-to-door convenience, autonomous vehicles are believed to change people's mode choice, especially their attitude towards public transport. Some argue that public transport will be threatened and even substituted by SAVs and DRS in some cases because they are much more convenient with only slightly higher prices. Others believe that public transport will be more attractive in combination with SAVs because they fill the gap of the last-mile problem in public transport. Since the scale of each effect could be different, it is necessary to distinguish between several scenarios to discuss the net effects of mode choice. Note that such classification scenarios are just conceptual and the quantitative standards used below are only for reference.

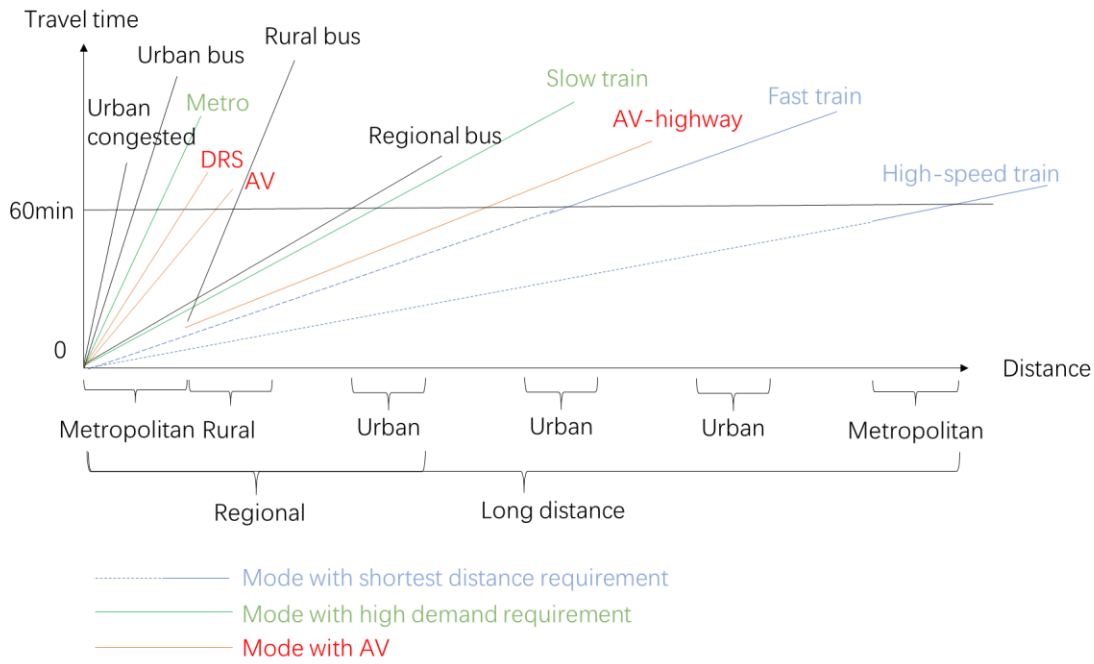
Three zonal levels are distinguished in transportation from a spatial perspective: Urban, regional and long-distance travelling. The urban level refers to trips up to 30 km and highways usually are not included. Regional travelling includes rural travel as well as intercity travel with distance of 30-200 km. Long-distance level is the rest with distance longer than 200 km except those intercontinental travel. Only automobile and public transport are considered here since other modes like biking, walking, are relatively less relevant. Also, the main considerations are travel time and monetary cost, while other issues such as emission are not mentioned in the analysis.

Long distance travel is least affected by autonomous vehicles, because the critical travel speed is still not as competitive as public transport, e.g. fast trains, high-speed trains, air travel, etc. But it still it depends on the choice set of alternative modes. For central and western Europe, where the railway network is already developed to compete against other modes (night busses and air travel) in long-distance travel, travelling by rail will become more attractive. On the one hand, train tickets will be cheaper once rail industry also realizes autonomous driving. On the other hand, slow regional trains are likely to be at least partly redundant, which would increase capacity and enhance punctuality for the remaining fast long-distance trains that share the same infrastructure. What's more, SAVs provide a competitive alternative to facilitate convenient inter-modal travel. However, for countries that do not support high-speed rails and rely on air transport or night buses to offer long-distance connections, AVs have more advantages. It is cheaper and more stable than air transport. Furthermore, it is more convenient and comfortable than night busses. However, these two are usually not among the recipients of public transport subsidies. And such long-distance travels are usually more flexible to avoid peak-hour traffic. Therefore, demand shifts from air travel and night buses towards AVs will have little impact on general public transport subsidy schemes.

Regional travel may be the field that AVs become most likely to compete with public transport. For dispersed rural transport with low bundled demand, rural bus operation is usually cost recovery itself and relies largely on public subsidies. An SAV fleet will likely meet the local mobility demand in a much more efficient way. For inter-city travel, automobiles are currently competing with public transport. In uncongested situations, automobiles could be faster and more comfortable than regional busses as well as slow regional train connections. Autonomous vehicles strengthen such advantages through reducing highway congestion remarkably. The capacity increase could absorb most of the shifts from train travel, making it possible to reduce slow regional train frequencies without bringing highway congestion. But public transport has an advantage over cars in its lower monetary costs for users, either when there is sufficient demand or when it is largely subsidized. When the demand for public transport has shifted to automobiles, it could be inefficient to operate such mass transits for only a small number of low-income people. Regional bus lines could be a compromise between operating efficiency and user affordability, and function as a substitute for cancelled train connections.

Urban travel might be the most complicated case, because the demand varies during the day, reaching its maximum during peak hours in the morning and late afternoon. Capacity increases on urban streets are much smaller compared with an increase on highways. It is hardly possible for autonomous vehicles to absorb all the shifts from urban public transport given current mode share. In peak hours, public transport is still needed to keep an optimal traffic flow. Furthermore, autonomous vehicles reduce parking spaces and increase land use of other functions in city centres, which brings more activities and travel demand in the urban scenario. Such an increase could offset the capacity increase and cities, especially metropolitans might rely even more on public transport as mass transit in peak hours. In off-peak hours, public transport might not have sufficient demand to keep frequent operations without more subsidies, even though that operating costs could be largely reduced when no human drivers' income is needed. One solution from an operators' view is to run with smaller vehicles. The other alternative from a low-income users' perspective, when public transport service is no longer offered, is to choose dynamic ride sharing. One thing to notice is that regional travel usually involves a part of the trip on urban roads. A huge loss of capacity at city entrances could bring congestion to the city as a result from massive non-local vehicles. Some kind of road tolls could be applied to promote park-and-ride, so that regional commuters could make the most out of highway capacity and then turn to urban public transport inside the destination city to avoid causing congestion.

Figure 14: Necessity of public transport in AV systems



To sum up, public transport is still a necessity in autonomous vehicles' world because of various reasons. For urban travel, public transport is needed because the network capacity isn't big enough to offer mobility service through automobile for everyone. As shown in Figure 14, urban congestion leads to longer travel time for both automobile as well as bus users and is a problem to be solved just like today. For regional travel, AVs have obvious advantage in travel time and comfort. Note that the line for AV on highway doesn't start from the original point because of uncertainty of the time spent on urban roads before inter-city commuters enter highway. The line could move up and down but the slope, i.e., average speed on highway, is relatively correct to be between slow train and fast train. Public transport exists mostly for the benefit of low-income people for regional travellers. For long-distance travel, public transport is needed because of its undoubted speed advantage. Such advantage only exists in long-distance travel because they have minimal distance requirement. For example, a fast-train connecting Zurich and Basel won't stop in between so they are not an option for commuters living in between. That's why part of the lines is dashed in the graph.

Others necessary public transport in the AV system includes those for special landscape or usages, such as ferry, cable car, tourism bus, etc. They are the minority and are affected by autonomous vehicle only slightly. Therefore, these are not in the scope of further analysis.

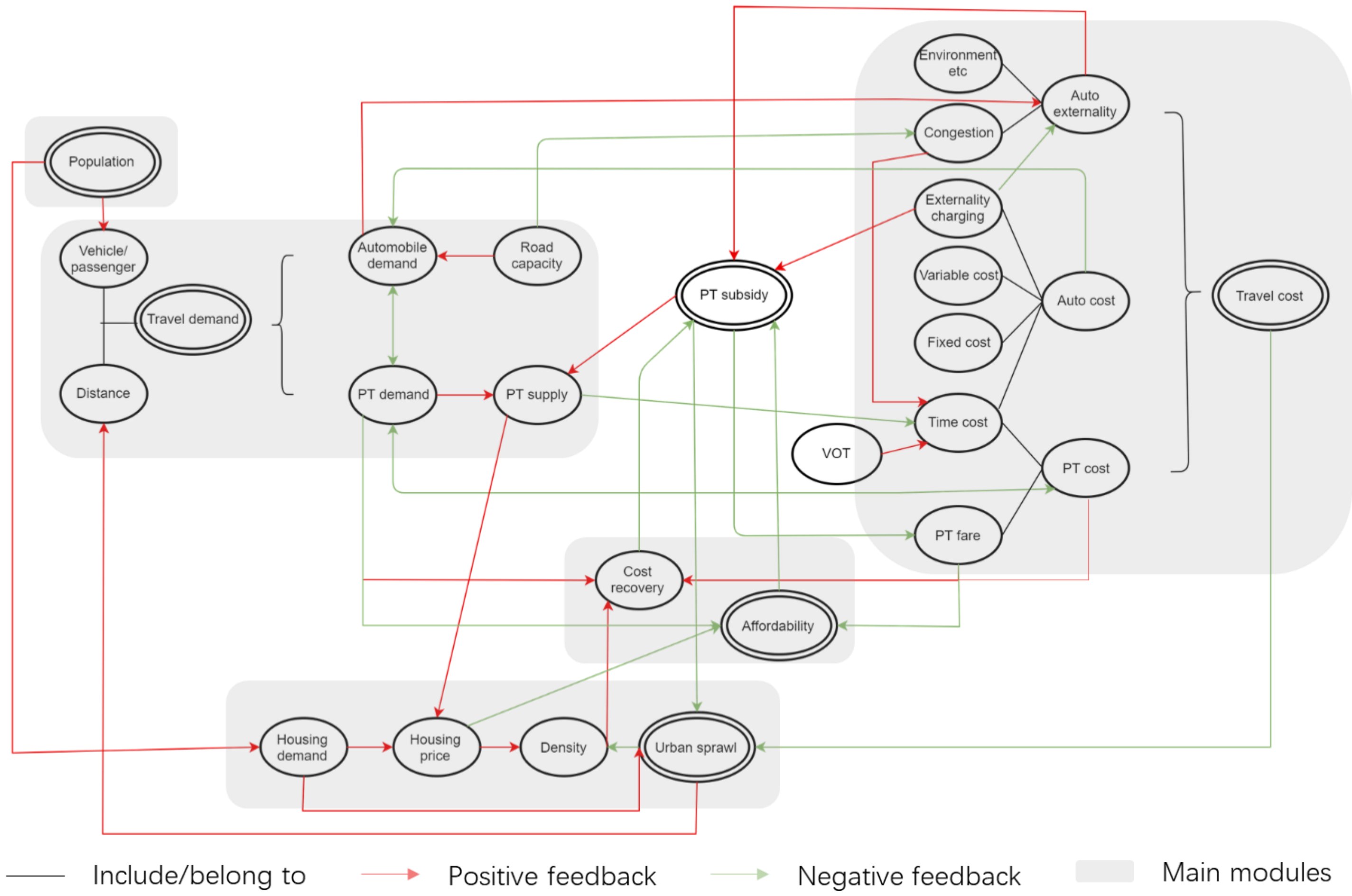
6.2 An interaction diagram for PT subsidy

To better illustrate the mechanism of public transport subsidies, an interactive diagram is used as shown in Figure 15, which serves as a summary for Chapter 2 and 3. With subsidy in the centre, there are 5 factors in the surrounding and they form a dynamic equilibrium through their interactions.

The most intuitive interaction exists when subsidy becomes a necessity to offer basic mobility service at an affordable fare level. When the public transport demand is not sufficient to cover the operating costs, it becomes a win-lose case between the operators and users. Either operators suffer a financial loss to maintain the low fare level, or the users suffer unaffordability. Public transport subsidy then becomes a public obligation to balance the loss by either or both parties. In the first case, operation subsidy is granted as the subsidy for an unprofitable level in the London bus case. In the second case, user subsidy is granted as the low-income targeted concession in Bogota.

However, travel demand and costs for public transport are always in a dynamic equilibrium. and they make up another two modules in interaction with public transport subsidy. Travel demand is distinguished between automobile and public transport, while other modes are omitted to simplify. The first interaction happens between demand and cost of public transport and subsidy, based on the scale effect in public transport operation. When public transport demand is sufficient to cover the costs, public transport promotes the shift from original equilibrium towards the social optimum. It encourages more frequent or/and densified public

Figure 15: Interactive diagram of PT subsidy



transport supply and improves a whole society in terms of welfare. The second interaction happens between the demand of automobiles and costs of public transport. Change on each one of it might have an effect on the other three. Travel service by automobile and public transport are two substitutes, which justifies public transport subsidy as the second-best pricing when there's excessive demand for automobile. However, such a substitution effect might not be as strong as expected given the relatively low cross-elasticity between the two modes. That is when first best pricing is more favoured to solve the problem. Revenues from automobile externality charging could be further used as a source for public transport subsidy to support other usage such as to offer concessions for low-income groups.

Population is less relevant to public transport subsidy as an external module, but it's critical considering that it keeps offering the initial dynamic into the system even when everything else is kept stable. Firstly, population growth inevitably increases total travel demand. Secondly, population growth involves the last module in the relation schema - spatial effects. As illustrated in the Beijing case, an increase in population (both naturally as well as immigration based) brings new spatial demand in housing that stimulates urban sprawl. Urban sprawl then interacts with travel demand, cost and subsidy actively, such as longer commuting distances, less densified built-up areas in suburban zones and higher demands for public transport subsidy.

6.3 Insights into public transport subsidy schemes

Autonomous vehicles change the direct cost and demand for automobile and public transport travel, which in turn changes the profitability of public transport. All these changes are in need of public transport subsidies to balance the economic efficiency and basic service obligations. In this section, some recommendations for public transport subsidy policies will be provided based on the combination of the previous two sections, i.e., where public transport is needed and how subsidy functions in different scenarios.

The main direct changes brought by autonomous vehicles are illustrated in Figure 16. While different directions of impacts could be identified, several general effects can be summarized.

First of all, user affordability of public transport will be generally improved. As analysed in section 5.3, public transport operation costs would be much lower from an operator's view once no drivers are needed anymore. However, the same effect goes to SAV. Costs for SAV could be much lowered without human drivers' income compared with current taxi service. The difference gets to be smaller in general. In a less-developed country where low-income people constitute a large portion of the population, the slight cost advantage of public transport might still be attractive to enough amount of people. Such situation also exists in the current world. The slightly higher charging of TransMilenio compared with Buseta has stopped many low-income people from using the faster BRT system. For societies like this, it is actually quite similar to today and still makes sense to maintain the public transport operation at an affordable level through subsidies. However, in a generally richer society, the price advantage could be valued only by the small group with the lowest income. It would be cost-inefficient to operate a fixed schedule public transport service at a loss. A simple estimation could be conducted to compare the cost difference to maintain the public transport service and the cost to cover their transport demand through DRS. While maintain public transport service usually requires keeping the whole public transport network for a convenient mobility, in a low-demand scenario it might cost a lot of resource but waste a lot of capacity. For an extreme low demand, it might be that subsidizing usage of ride sharing could cost less than subsidizing operation of bus service but offer better mobility services. What's more, to help the minor group of the lowest income people in a relatively rich society, general redistributive policies are needed. These people might not only need financial aid in mobility but also other basic living materials such as food, housing, etc. Other redistributive policies might work better to help them with what they needed most such as raising the minimal living standard considering the absence of public transport, or more regressive tax, etc.

Secondly, second best pricing argument becomes less convincing to support public transport subsidy in most cases. On the one hand, original excessive demand might not be causing so much externality as before so there is no need to shift them to public transport by lowering the fare level. A typical scenario would be subsidizing regional train passengers to reduce vehicles on highways. Such subsidies are common today, but might no longer apply in AV-systems. On the other hand, excessive usage of automobiles and external costs might still exist especially in urban scenarios. But using public transport subsidies to adjust mode share would not be as effective as they are today because of two reasons. Firstly, first best pricing would be easier to implement. Travel data on time, location, vehicle type and number of passengers would be more available to charge each vehicle's congestion and emission contribution more precisely, especially for SAV users. For example, a congestion fee could be flexibly calculated according to actual or estimated congestion levels and be used as feedback to users. Such fees could even favour ride sharing. Users would be motivated to turn to public transport or another time to travel. First best pricing revenues could be used as a subsidy to support basic public transport operation in non-peak hours. Secondly, differences in monetary costs between public transport and automobiles, especially DRS, would be smaller. However, time savings in automobile usage, plus other convenience and comfort, will make automobile much more advantageous than public transport. The cross elasticity between these two is expected to be even smaller than the level today. The effect of lower public transport prices would be too little to motivate mode shifts.

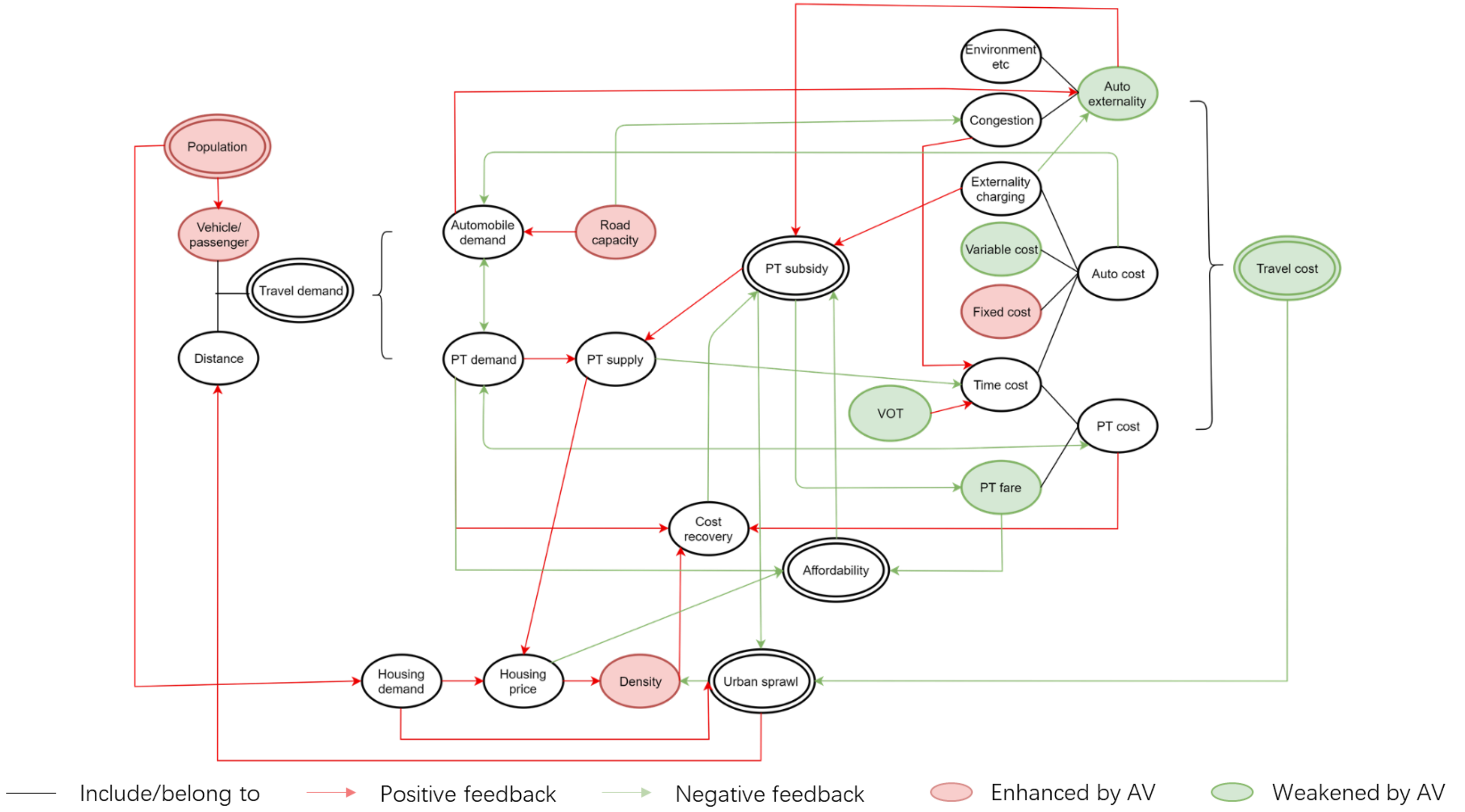
While cross elasticities are insensitive to monetary costs, an alternative is to reduce time costs. In the autonomous vehicle system, reducing access and egress distance would be less effective since last-mile connections would be served by SAVs. The value of time in automobile is much smaller than walking and the speed of automobile is much higher than walking. Therefore, the Mohring effect would contribute only a little to the scale effect. Nonetheless, autonomous vehicles only reduce economies of density in public transport. Shorter headways and direct connections still have its reducing effect on time costs. However, demand for urban public transport will vary more in an autonomous vehicles system, depending on whether it is peak hour or not. Adding more services in peak hour could mean more idle vehicles in non-peak hour and result in a waste of capacity and resource. Public transport operators might not have enough incentives to increase services to attract automobile users.

While the monetary costs of public transport and automobiles are getting closer in an autonomous vehicles system, automobiles have more absolute advantages over time costs and service level. Such differences make public transport and automobiles less substitutive to each other so that pricing instruments are less effective to balance the demand. Public transport subsidy, as a pricing instrument from the public transport side, is also less effective to adjust the mode share.

However, what could be more substitutive is the usage of ride sharing. Ride sharing could be seen as the substitutive good for both PAV/SAV as well as public transport. It combines the advantages of both car and public transport. When ride sharing happens between two or three passengers, it might still be seen as more like automobile usage. However, ride sharing with 8 people would be more similar to minibus. Ride sharing with 20 people on a fixed route and fixed time in peak hours could be seen as an adapted work bus in autonomous vehicles systems. Ride sharing with different vehicle size becomes a substitute for automobile or public transport with flexible combination of advantages according to the scenarios' requirement. Smaller vehicle is more convenient but transport less collectively. Larger vehicle can be more efficient in peak hours but lose some of flexibility. It's a substitute good for both automobile and public transport to have intermediate levels of time cost and monetary cost for users, demand requirement for operators, as well as collective transport for the higher social welfare. In other words, it could be seen that ride sharing with different vehicle sizes could make the boundaries between private and public transport, individual and collective transport less distinct than before. Though demand for car and public transport could be more difficult to be adjusted by pricing instruments, subsidy could turn to those intermediate substitutive and try to keep a dynamic equilibrium with maximized social welfare.

What remains barely changed for public transport subsidy is the large infrastructure cost which could be too high or too risky for the market to bear. Developed countries might already have most of its rail network constructed. The speed of urbanization and population growth will also be much slower in the future decades to come. Infrastructure generally only needs small-scale maintenance, which could be more affordable to local governments, except for high-speed railways. In developing countries, current supply of infrastructure might already fall short of demand, and population will further grow. The country might need a nationwide plan of railway infrastructure construction. In such cases, infrastructure subsidy is critical for the economic development but also costly. While cities like Beijing can afford the investment, and keep the low transit fare at the same time, Bogota can only invest in infrastructure but no more in lower fares. Poorer countries, such in Africa, face even more demand for the future infrastructure costs since they have less now. But they also face larger shortage of financial funds because of slow economic growth. International assistance will still be needed for future decade.

Figure 16: Effects of AV in the interactive diagram

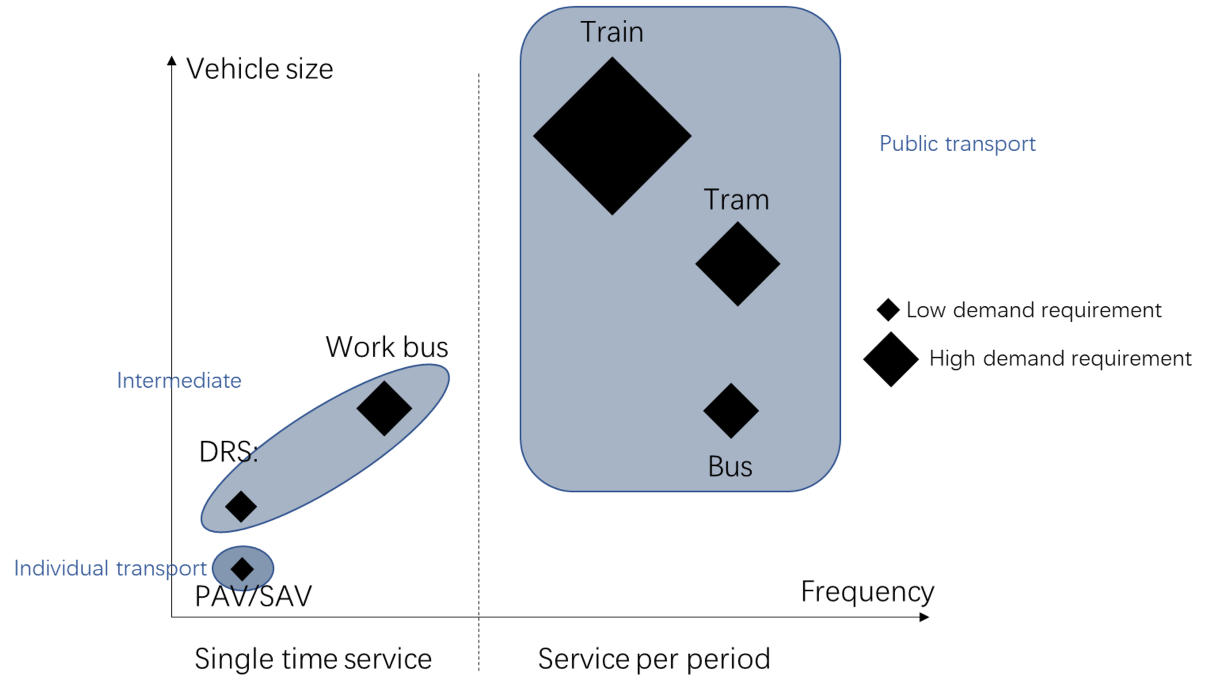


7 Conclusion

Subsidy, in essence, is a tool or external resource to mediate the imbalance between the demand and cost of private automobiles as well as public transport. For example, when the demand for private automobiles is too high, or the demand for public transport is insufficient to cover operating costs, or when costs for public transport are too high for certain groups, or when costs of private automobiles are not fully internalised.

The largest challenge for subsidy scheme in an AV-system is the less substitutive property between the two goods of car travel and public transport travel. The time costs for car travel could be much lower but the monetary costs might be only slightly different. Such comparison would make it more difficult to encourage people to change their travel behaviour through pricing with limited financial inputs.

Figure 17: Alternatives between individual private transport and collective public transport



However, AVs make the traditional car travel and public transport diverse more from each other but also provide other alternatives as the transition from car usage to traditional public transport (Figure 17). Ride sharing with small size vehicle functions more like individual car service. But ride sharing with large size vehicle would function more like traditional public transport.

Especially if the large group of shared riders have similar regular schedule and fix their time in the day, such ride sharing works a lot like the work bus today. Those quasi-public transport can be adjusted flexibly to offer more direct connections, reach higher occupancy rates and transport with fewer vehicles, i.e., resources better allocated to demand to reduce total costs.

In summary, while autonomous vehicles would weaken many effects of subsidizing conventional public transport, they also bring new substitutes to better realize these effects. Ride sharing with different vehicle sizes combine the advantage from car usage and public transport differently. They could function more efficiently because it is always offered on demand. Their demand could also be adjusted more easily through pricing because these services are more substitutive to each other. Hence, with mobility offered as service in the future AV-systems, recipient of subsidy should also turn to those flexible and on-demand single service to be more efficient.

8 Reference list

Alsnih, R. and D. A. Hensher (2003) The mobility and accessibility expectations of seniors in an aging population, *Transportation Research Part A: Policy and Practice*, **37** (10), 903–916.

Amaral, M., S. Saussier and A. Yvrande-Billon (2013) Expected number of bidders and winning bids evidence from the london bus tendering model, *Journal of Transport Economics and Policy*, **47** (1), 17–34.

Anderson, J., N. Kalra, K. Stanley, P. Sorensen, C. Samaras and O. Oluwatola (2016) *Autonomous Vehicle Technology: A Guide for Policymakers*, Rand Corporation, Santa Monica.

Bansal, P., K. Kockelman and A. Singh (2016) Assessing public opinions of and interest in new vehicle technologies: An Austin perspective, *Transportation Research Part C: Emerging Technologies*, **67**, 1–14. Retrieved from http://dx.doi.org/10.1016/j.trc.2016.01.019

Bergenhem, C., H. Pettersson and E. Coelingh (2012) Overview of platooning systems, In *Proceedings of the 19th ITS World Congress, Oct 22-26, Vienna, Austria (2012)* (pp. 1–7).

Bischoff, J. and M. Maciejewski (2016) Simulation of city-wide replacement of private cars with autonomous taxis in Berlin, *Procedia Computer Science*, **83** (Ant), 237–244.

Bocarejo, J. P. and D. R. Oviedo H. (2012) Transport accessibility and social inequities: a tool for identification of mobility needs and evaluation of transport investments, *Journal of Transport Geography*, **24**, 142–154.

Bocarejo, J. P., I. Portilla and M. A. Pérez (2013) Impact of Transmilenio on density, land use, and land value in Bogotá, *Research in Transportation Economics*, **40** (1), 78–86.

Boesch, P. M., F. Ciari and K. W. Axhausen (2016) Autonomous vehicle fleet sizes required to serve different levels of demand, *Transportation Research Record: Journal of the Transportation Research Board*, **2542**, 111–119.

Boitani, A. and C. Cambini (2006) To bid or not to bid, this is the question: the Italian experience in competitive tendering for local bus services, *European Transport*, (33), 41–53.

Borck, R. (2006) The Political Economy of Urban Transit, In *OECD Round Table on "Privatisation and Regulation of Urban Transit Systems"* (pp. 27–42).

Bösch, P. M., F. Becker, H. Becker and K. W. Axhausen (2017) Cost-based analysis of autonomous mobility services, *Transport Policy*, **64** (September 2017), 76–91.

Brakman, S., H. Garretsen and C. van Marrewijk (2009) *The New Introduction to Geographical Economics*, Cambridge University Press, Cambirdge.

Brown, A., J. Gonder and B. Repac (2014) An analysis of possible energy impacts of automated vehicles, In G. Meyer & S. Beiker (Eds.), *Road Vehicle Automation* Springer International Publishing, Cham. Retrieved from http://link.springer.com/10.1007/978-3-319-60934-8

Brueckner, J. K. (2003) *Transport Subsidies, System Choice, and Urban Sprawl*, (No. 1090).

Brueckner, J. K., J. F. Thisse and Y. Zenou (1999) Why is central Paris rich and downtown Detroit poor? An amenity-based theory, *European Economic Review*, **43** (1), 91–107.

Burns, L. D., W. C. Jordan and B. a. Scarborough (2013) Program on Sustainable Mobility The Earth Institute , Columbia University, 1–43.

Cantillon, E. and M. Pesendorfer (2005) *Auctioning bus routes: The London experience*, (P. Cramton, Y. Shoham, & R. Steinberg, Eds.), *Combinatorial Auctions* MIT Press, Cambirdge.

Cervero, R. (1984) Cost and performance impacts of transit subsidy programs, *Transportation Research Part A: General*, **18** (5–6), 407–413.

Cervero, R. (2005) Progressive transport and the poor: Bogota's bold steps forward, *Access Magazine*, **1**, 1–17.

Chen, T. D., K. Kockelman and J. P. Hanna (2016) Operations of a shared, autonomous, electric vehicle fleet: Implications of vehicle & charging infrastructure decisions, *Transportation Research Part A: Policy and Practice*, **94**, 243–254.

Chen, Y., A. Ardila-Gomez and G. Frame (2017) Achieving energy savings by intelligent transportation systems investments in the context of smart cities, *Transportation Research Part D: Transport and Environment*, **54** (October), 381–396.

Cohen, B. (2006) Urbanization in developing countries: Current trends, future projections, and key challenges for sustainability, *Technology in Society*, **28** (1–2), 63–80.

EEA (2007) *Size, Structure and Distribution of Transport Subsidies in Europe*, Copenhagen.

Else, P. K. (1985) Optimal pricing and subsidies for scheduled transport services, *Journal of Transport Economics and Policy*, **19** (3), 263–279.

Fagnant, D. J. and K. Kockelman (2015) Preparing a nation for autonomous vehicles: Opportunities, barriers and policy recommendations, *Transportation Research Part A: Policy and Practice*, **77**, 167–181.

Fagnant, D. J. and K. Kockelman (2018) Dynamic ride-sharing and fleet sizing for a system of shared autonomous vehicles in Austin, Texas, *Transportation*, **45** (1), 143–158.

Fagnant, D. J., K. Kockelman and P. Bansal (2015) Operations of Shared Autonomous Vehicle Fleet for Austin, Texas, Market, *Transportation Research Record: Journal of the Transportation Research Board*, **2536**, 98–106. Retrieved from http://trrjournalonline.trb.org/doi/10.3141/2536-12

Frankena, M. W. (1973) Income distributional effects of urban transit subsidies, *Journal of Transport Economics and Policy*, **7** (3), 215–230. Retrieved from http://www.jstor.org/stable/20052329

Frankena, M. W. (1987) Capital-biased subsidies, bureaucratic monitoring, and bus scrapping, *Journal of Urban Economics*, **21** (2), 180–193.

Gilbert, A. (2008) Bus rapid transit: Is Transmilenio a miracle cure?, *Transport Reviews*, **28** (4), 439–467.

Glaister, S. (1974) Generalised consumer surplus and public transport pricing, *The Economic Journal*, **84** (336), 849–867.

Gucwa, M. A. (2014) the Mobility and Energy Impacts of Automated Cars, 79.

Guzmán, L. A., D. Oviedo, C. Rivera and S. Cardenas (2016) *Accessibility , affordability and poverty : Assessing public transport subsidies in Bogota*,.

Gwilliam, K. (2008) A review of issues in transit economics, *Research in Transportation Economics*, **23** (1), 4–22.

Haboucha, C. J., R. Ishaq and Y. Shiftan (2017) User preferences regarding autonomous vehicles, *Transportation Research Part C: Emerging Technologies*, **78**, 37–49.

Hars, A. (2016) *Top misconceptions of autonomous cars and self-driving vehicles*, *Inventivio GmbH* (Vol. 9). Retrieved from http://www.driverless-future.com/?page_id=774

Hayes, B. (2011) Leave the driving to it, *American Scientist*, **99** (5), 362–366.

Hensher, D. A. and I. P. Wallis (2005) Competitive tendering as a contracting mechanism for subsidising transport: The bus experience, *Journal of Transport Economics and Policy*, **39** (3), 295–321.

Hernandez, C. and T. Quiros (2016) *Balancing Financial Sustainablility and Affordability in Public Transport: the Case of Bogota, Colombia*,.

Hidalgo, D., L. Pereira, N. Estupiñán and P. L. Jiménez (2013) TransMilenio BRT system in Bogota, high performance and positive impact - Main results of an ex-post evaluation, *Research in Transportation Economics*, **39** (1), 133–138. Retrieved from http://dx.doi.org/10.1016/j.retrec.2012.06.005

International, S. (2016) *Taxonomy and Definitions for Terms Related to Driving Automation Systems for On-Road Motor Vehicles*,.

Ison, S. and T. Rye (2008) *The Implementation and Effectiveness of Transport Demand Management Measures*, Routledge, London.

Jackson, R. (1975) Optimal subsidy for public transit, *Journal of Transport Economics and Policy*, **9** (1), 3–15.

Juliussen, E. and J. Carlson (2014) Autonomous Cars - Not if, but when, *IHS Automotive*.

Kaufmann, T. (2012) *Bogota in Bewegung: Nachhaltige Verkehrslösungen für das 21. Jahrhundert*, LIT Verlag, Wien.

Kennedy, D. (1996a) London bus tendering: A welfare balance, *Transport Policy*, **2** (4), 243–249.

Kennedy, D. (1996b) *The Economics of London Bus Tendering*, The London School of Economics and Political Science.

Kesting, A., M. Treiber and D. Helbing (2009) Enhanced intelligent driver model to access the impact of driving strategies on traffic capacity, *Philosophical Transactions of the Royal Society of London A: Mathematical, Physical and Engineering Sciences*, **368** (1928), 4585–4605.

Kockelman, K., S. Boyles, P. Stone, D. J. Fagnant, R. Patel, M. W. Levin, … J. Li (2016) An Assessment of Autonomous Vehicles: Traffic Impacts and Infrastructure Needs. Final Report (FHWA 0-6847-1), *Center for Transportation Research the University of Texas at Austin*, 182. Retrieved from http://library.ctr.utexas.edu/ctr

Krueger, R., T. H. Rashidi and J. M. Rose (2016) Preferences for shared autonomous vehicles, *Transportation Research Part C: Emerging Technologies*, **69**, 343–355.

Krugman, P. (1991) Increasing returns and economic geography, *Journal of Political Economy*, **99** (3), 483–499.

Le Vine, S., A. Zolfaghari and J. Polak (2015) Autonomous cars: The tension between occupant experience and intersection capacity, *Transportation Research Part C: Emerging Technologies*, **52**, 1–14.

Levin, M. W. and S. Boyles (2016) A multiclass cell transmission model for shared human and autonomous vehicle roads, *Transportation Research Part C*, **62**, 103–116.

Litman, T. (2006) *Parking management: strategies, evaluation and planning*, Victoria.

Litman, T. (2018) *Autonomous Vehicle Implementation Predictions: Implications for Transport Planning*, *Victoria Transport Policy Institute*. https://doi.org/10.1613/jair.301

Lutin, J. M., A. L. Kornhauser and E. Lerner-Lam (2013) The revolutionary development of self-driving vehicles and implications for the tranportation engineering profession, *ITE Journal*, **83** (7), 28–32.

Mallard, G. and S. Glasiter (2008) *Transport Economics: Theory, Application and Policy*, Palgrave Macmillan, Basingstoke.

Meyer, J., H. Becker, P. M. Bösch and K. W. Axhausen (2017) Autonomous vehicles: The next jump in accessibilities?, *Research in Transportation Economics*, **62**, 80–91.

Millard-Ball, A. (2018) Pedestrians, autonomous vehicles, and cities, *Journal of Planning Education and Research*, **38** (1), 6–12.

Mohring, H. (1972) Optimization and scale economies in urban bus transportation, *The American Economic Review*, **62** (4), 591–604.

Nash, C., P. Bickel, R. Friedrich, H. Link and L. Stewart (2002) The environmental impact of transport subsidies, *OECD Workshop on Environmentally Harmful Subsidies*, Paris, November, 2002.

NHTSA (2008) National Motor Vehicle Crash Causation Survey Report to Congress, *National Highway Transport Safety Agency*, Springfield.

Ortuzar, J. de D. and L. G. Willumsen (2011) *Modelling Transport*, Wiley, Chichester.

Parry, I. W. H. and K. A. Small (2009) Should urban transit subsidies be reduced?, *American Economic Review*, **99** (3), 700–724.

Pocket, J. (1998) *Modern Economic Systems and their Transformation*, Macmillan, Basingstoke.

PPIAF (2006) Urban Bus Toolkit: Tools and Options for Reforming Urban Bus Systems, https://ppiaf.org/sites/ppiaf.org/files/documents/toolkits/UrbanBusToolkit/assets/3/3.6/3.6(i).html, PPIAF World Bank, Washington, 2006.

Preston, J. and T. Almutairi (2013) Evaluating the long term impacts of transport policy: An initial assessment of bus deregulation, *Research in Transportation Economics*, **39** (1), 208–214.

Pucher, J., A. Markstedt and I. Hirschman (1983) Impacts of subsidies on the costs of urban public transport, *Journal of Transport Economics and Policy*, **17** (2), 155–176.

Reeven, P. Van (2008) Subsidisation of urban public transport and the Mohring effect, *Transport Economics and Policy*, **42**, 349–359.

Rodriguez, C., J. M. Gallego, D. Marinez, S. Montoya and T. Peralta-Quiros (2015) Examining the implementation and labor market outcomes of targeted transit subsidies: SISBEN subsidy for Bogota's urban poor, *Transportation Research Record*, **2581**, 9–17.

Ross, C. and S. Guhathakurta (2017) Autonomous vehicles and energy impacts: A scenario analysis, *Energy Procedia*, **143**, 47–52.

Rye, T. (2008) *The Implementation and Effectiveness of Transport Demand Management Measures: An International Perspective*, Routledge, London.

Sandoval, E. E. and D. Hidalgo (2004) TransMilenio: A high capacity - low cost bus rapid transit system developed for Bogota, Colombia, 2nd *International Conference on Urban Public Transportation Systems*, Virginia, April 2004.

Schipper, L. (2002) Sustainable urban transport in the 21st Century: A new agenda, *Transportation Research Record*, **1792** (2), 12–19.

Scholz, T., A. Schmallowsky and T. Wauer (2007) Auswirkungen eines Allgemeinen Tempolimits auf Autobahnen im Land Brandenburg, *Kommunale und regionale Verkehrsplanung und Verkehrstechnik*, Land Brandenburg, Potsdam

Serebrisky, T., A. Gómez-Lobo, N. Estupiñán and R. Muñoz-Raskin (2009) Affordability and subsidies in public urban transport: What do we mean, what can be done?, *Transport Reviews*, **29** (6), 715–739.

Shladover, S., D. Su and X.-Y. Lu (2012) Impacts of Cooperative Adaptive Cruise Control on Freeway Traffic Flow, *Transportation Research Record: Journal of the Transportation Research Board*, **(2324**), 63–70.

Sivak, M. and B. Schoettle (2015) Road safety with self-driving vehicles: General limitations and road sharing with conventional vehicles, *Report No. UMTRI-2015-2*, Transportation Research Institute, University of Michigan, Ann Arbor.

Small, K. A. and E. T. Verhoef (2007) *The Economics of Urban Transportation*, Routledge, London.

Small, K. A., E. T. Verhoef and R. Lindsey (2007) *The Economics of Urban Transportation*, Routledge, Abingdon.

Steck, F., V. Kolarova, F. Bahamonde-Birke, S. Trommer and B. Lenz (2018) How autonomous driving may affect the value of travel time savings for commuting, *Transportation Research Record*, 1–18.

Stern, R. E., S. Cui, M. L. Delle Monache, R. Bhadani, M. Bunting, M. Churchill, N. Hamilton, D. B. Work (2018) Dissipation of stop-and-go waves via control of autonomous vehicles: Field experiments, *Transportation Research Part C: Emerging Technologies*, **89**, 205–221.

Su, Q. and J. S. Desalvo (2008) The effect of transportation subsidies on urban sprawl, *Journal of Regional Science*, **48** (3), 567–594.

Sullivan, A. O. (2012) *Urban Economics*, McGraw-Hill/Irwin, New York.

Taylor, B. D. and K. Samples (2002) Jobs, jobs, jobs: Political perceptions, economic reality, and capital bias in U.S. transit subsidy policy, *Public Works Management & Policy*, **6** (4), 250–263.

Tirachini, A. and D. A. Hensher (2012) Multimodal transport pricing: First best, second best and extensions to non-motorized transport, *Transport Reviews*, **32** (2), 181–202.

Transport for London (2015) London’s bus contracting and tendering process, *Report from Transport for London*, Transport for London, London.

Transport for London (2017a) Annual report and statement of accounts annual report and statement of accounts, *Report from Transport for London*, Transport for London, London.

Transport for London (2017b) Travel in London, *Report 9*, Transport for London, London.

Tscharaktschiew, S. and G. Hirte (2012) Should subsidies to urban passenger transport be increased? A spatial CGE analysis for a German metropolitan area, *Transportation Research Part A: Policy and Practice*, **46** (2), 285–309.

United Nations (2015) World population ageing, *ST/ESA/SER.A/390*, United Nations, New York.

United Nations (2017) World population prospects: The 2017 revision key findings and advance tables, *ESA/P/WP/248*, United Nations, New York.

van den Berg, P., T. Arentze and H. Timmermans (2011) Estimating social travel demand of senior citizens in the Netherlands, *Journal of Transport Geography*, **19** (2), 323–331.

Wadud, Z., D. MacKenzie and P. Leiby (2016) Help or hindrance? The travel, energy and carbon impacts of highly automated vehicles, *Transportation Research Part A: Policy and Practice*, **86**, 1–18.

White, P. (1995) Deregulation of local bus services in great britain: An introductory review: Foreign summaries, *Transport Reviews*, **15** (2), 185–209.

White, P. (2010) The conflict between competition policy and the wider role of the local bus industry in Britain, *Research in Transportation Economics*, **29** (1), 152–158.

Zhang, M., X. Meng, L. Wang and T. Xu (2014) Transit development shaping urbanization: Evidence from the housing market in Beijing, *Habitat International*, **44**, 545–554.

Zhang, W., S. Guhathakurta, J. Fang and G. Zhang (2015) Exploring the impact of shared autonomous vehicles on urban parking demand: An agent-based simulation approach, *Sustainable Cities and Society*, **19**, 34–45.

Zhao, P. (2010) Sustainable urban expansion and transportation in a growing megacity: Consequences of urban sprawl for mobility on the urban fringe of Beijing, *Habitat International*, **34** (2), 236–243.

Zhao, P. (2011) Managing urban growth in a transforming China: Evidence from Beijing, *Land Use Policy*, **28** (1), 96–109.

Zhao, P. (2013) Too complex to be managed? New trends in peri-urbanisation and its planning in Beijing, *Cities*, **30** (1), 68–76.

Zhou, J., E. Murphy and Y. Long (2014) Commuting efficiency in the Beijing metropolitan area: An exploration combining smartcard and travel survey data, *Journal of Transport Geography*, **41**, 175–183.