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Will public transport be relevant in a self-driving future? A demand model simulation of four scenarios for Stockholm, Sweden

Erik Almlöf [a,*], Mikael Nybacka[a,b], Anna Pernestål[a]

[a]*KTH Royal Institute of Technology, Integrated Transport Research Lab, Drottning Kristinas väg 40, 114 28 Stockholm, Sweden*
[b] *Vehicle Engineering and Solid Mechanics, KTH Royal Institute of Technology, SE-100 44 Stockholm, Sweden*

Abstract

The public sector makes long-term investments in for example tram rail lines and highways based on forecasts of future travelling but generally do not consider the impacts of self-driving technology as a factor. Several papers have presented transport system wide simulations with self-driving cars, exploring changes in mode choice, energy demand or the potential for sharing. Demand traffic models have been used in several studies, looking at modal choice changes, but the general assumption is that the public transport service remains unchanged, despite a large potential for governments to enhance service or reduce costs. This paper examines the effects of self-driving technology on the transport system with Stockholm, Sweden as a case study, looking at four scenarios which were developed with input from 130 transport professionals from industry, academia and the public sector. Each of the scenarios include one "car" and one "public transport" mode, looking at changes in e.g. modal choice and person kilometers traveled. The national demand model Sampers is used for evaluation. The results indicate a decrease in walking and bicycling in all scenarios and a decrease in public transport travelling in scenarios with a taxi-like car service. Although this result would mean a shift from public transport to car travel, the majority of travel to and from central parts of Stockholm were still made by public transport.

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Keywords: Autonomous vehicle; Public transport; Travel demand modelling

* Corresponding author. Tel.: +46 72 148 63 87.
E-mail address: ealmlof@kth.se

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1. Introduction

The impact of self-driving technology on the transport system remains uncertain. Milakis et al. (2017) outlines some aspects that may increase (e.g. vehicle kilometers traveled) or decrease (e.g. travelers injured) but the extent of the changes are uncertain (Pernestål Brenden and Kristoffersson, 2018). Earlier studies have modelled the transport system using transport models, modeling changes in demand and/or modal choice (Zhao and Kockelman, 2018, Lu et al., 2018 or Harper et al., 2018), whilst others have used system dynamics tools, see for example Puylaert et al. (2018). A common conclusion is an increase in car travel, due to increased accessibility for groups who previously have not had access to cars and/or increase car attractiveness due to a more productive use of travel time. An important factor influencing the levels of congestion and vehicle kilometers travelled is the level of sharing either vehicles and/or trips (Pernestål Brenden and Kristoffersson, 2018).

One major assumption made by previous modeling studies are that the public transport system remains unchanged. However Pernestål Brenden and Kottenhoff (2018) describes many possibilities for public transport to evolve substantially by the use of self-driving technology. The potential can be seen in public trials being conducted all over the world (see for example www.easymile.com).

In this paper impacts of self-driving technology is explored both for cars and for increasing service levels in public transport. This is done by studying four different scenarios with different applications of self-driving technology and compare the differences to the national transport authority's reference scenario. The main contributions of this paper is an increased understanding of the impacts from self-driving technology and vehicle sharing on e.g. vehicle kilometers traveled and modal share. To the best of our knowledge, no peer-reviewed research exists that has looked into scenarios with enhanced public transport, modeled with demand sensitive traffic software.

The paper is structured into six sections, including this introduction. In Section 2 the method used is presented. In Section 3 the parameters used in the simulations are presented and motivated. In Section 4 the results from the simulations are shown and in Section 5 they are compared to previous literature and the potential effects on the transport system are discussed. The paper ends with conclusions in Section 6.

2. Method

2.1. Development of the scenarios

The four scenarios used in this paper were developed during 2018/2019 with input from 130 professionals from the Swedish transport industry. The different actors were from academy, governmental institutions, public transport operators and consultants involved to differing degrees, discussing both general and technical aspects.

The paper is inspired by the work of Pernestål Brenden et al. (2017) who developed four scenarios along two dimensions, high/low sharing and active/passive government. In this paper these dimensions are explored along the lines of the two travel modes car and public transport in order to fit in to a traditional four step transport demand model. An overview of the scenarios is presented in Figure 1.

The sharing dimension is explored by implementing two different cases for the car mode. In the first case the car is still privately owned and may only be used for private trips within each household. However the car is accessible to people without a driver's license, e.g. children. In the second case sharing is introduced, and a taxi service based on driverless cars is assumed to be present. The taxi service can be summoned by anyone, and after the trip is complete the car will drive off to pick up the next passenger.

The governmental dimension is explored by using two different cases of public transport service. A passive government is represented by a case where the public transport system works essentially as today, but with a heavy increase in the level of service. An active government is represented by a case where a new type of on-demand public transport service is developed. In this service the main high-capacity lines are still intact but with a substitution of arterial lines with an on-demand shuttle service as described in Pernestål Brenden and Kottenhoff (2018) and used by e.g. The International Transport Forum (2017).

In the paper the following assumptions are used: Self-driving technology has been developed to SAE level 5 (SAE International, 2018) and has reached 100% market penetration. Self-driving technology is fully accepted by travelers, and infrastructure has been properly adjusted.

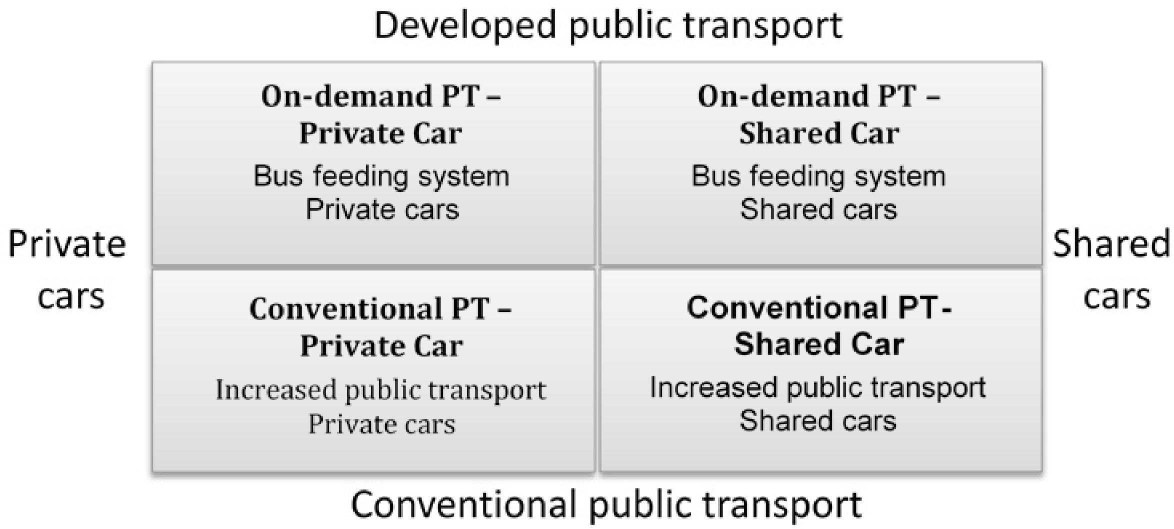

Figure 1. Schematic overview of the four different scenarios along the two dimensions sharing and development of public transport ("PT").

2.2. Modeling of the scenarios

The scenarios are modeled using the transport model Sampers (Beser and Algers 2002), in conjunction with PTV Visum for modelling public transport. This is also the model used by Stockholm Public Authority ("Stockholm PTA").

Sampers was developed by the National Transport Administration and has been used for almost twenty years in Sweden. It has been improved incrementally since the first launch and is generally accepted as a validated model (Sweco Society AB, 2018), used by national and regional actors, e.g. to make cost-benefit analysis in EU-funded projects.

Sampers is a four-step demand model which handles both calculation of total demand for transportation as well as assignment to the network, divided by mode: car (driver), car (passenger), public transport, walking and bicycling. The division between using the car as a driver and as a passenger is analogous to e.g. car pooling or kiss-and-ride, especially in families. This aspect is still present in the scenarios with self-driving technology and reflects willingness to share due to economic aspects.

Sampers consists of a wide variety of modules with both scripts written for the software as well as INRO's software Emme for calculation, assignment to the road network, as well as visualization. In this study Sampers is used for demand calculation, whereas calculation of travel times as well as assignment of travelers using public transport is done with PTVs Visum.

All scenarios are compared to the National Transport Authority's reference scenario, which is set in 2014 using data on e.g. population and road network. This reference scenario has been validated using data on observed travel in Stockholm (Sweco Society AB, 2018).

For an overall description of the model used in this paper, see Figure 2.

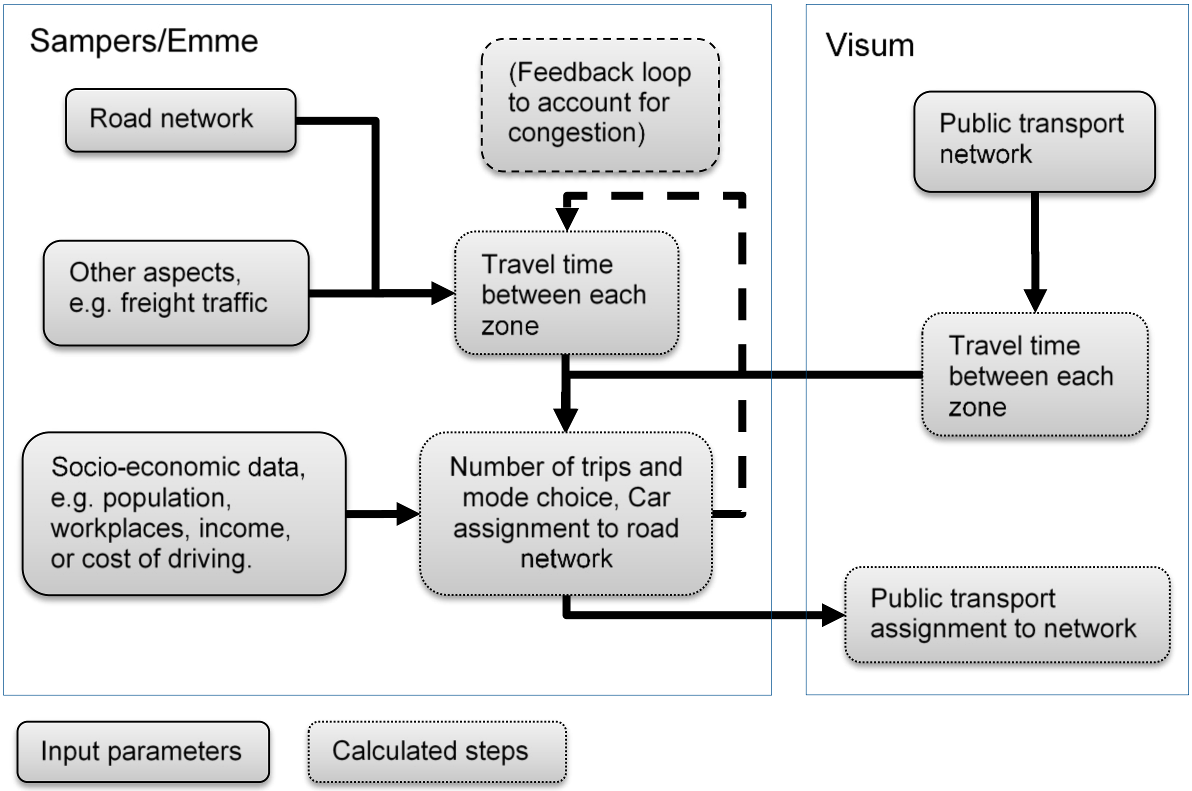

Figure 2. Overview of the Sampers/Visum model

3. Parameter settings

In this section the parameters used to implement the four scenarios are discussed. A summary of the parameters and their values in the different cases is presented in **Errore. L'origine riferimento non è stata trovata.**.

3.1. Value of Travel Time

The potential change in travelers' perception of the Value of travel time (VTT) has been the subject of a large number of papers (see e.g. Le Vine et al., 2015 or Singleton, 2019). Milakis et al. (2017) conclude that the effects on VTT are unknown and that there might be a tradeoff between comfort and road capacity due to motion sickness. Soteropoulos et al. (2019) show that a broad range of the value of travel time are used in previous studies, from no change to eliminating the perceived cost altogether. Due to the large uncertainty of the effects for both car and public transport travelers, this value has not been changed.

3.2. Capacity on highways

The potential for an increase of capacity in the road system is often cited as a major opportunity for self-driving and connected cars. However this is highly dependent on assumptions of distance between vehicles and cooperation between vehicles and infrastructure (Friedrich et al., 2018; Milakis et al., 2017; Ye and Yamamoto, 2018). Previous studies have also used varying changes in road capacity, from no change to an increase of the capacity of 100 %

depending on assumptions of safety and vehicle to vehicle communication capabilities (Soteropoulos et al., 2019). In this paper a doubling of the capacity on highways is assumed.

3.3. Capacity on local roads

Le Vine et al. (2015) identify that the travel comfort level is coupled with the capacity of the local road network, especially the capacity in intersections. The introduction of less risk-taking vehicles could even mean that capacity of local roads and intersections decrease compared to today (Milakis et al., 2017). As the capacity of local roads in urban areas to a large extent is determined by intersection capacity and interaction with other roads users no difference regarding capacity on local roads is assumed in this paper.

3.4. Running cost

Liu et al. (2017) show that the km cost is essential to attractiveness for a taxi service, with a cost per km of 0,27 € (1 € ≈1.1 US$) yielding 50 % modal share for an autonomous taxi service, compared to only a 10 % modal share using 0,67 € rate. For the Swedish context, Stjerna (2019) estimates a cost between 0,29 € (small sized car) up to 1,71 € (sports car) per kilometer (1 € ≈10.5 SEK) . Wadud (2017), examining the English context, uses numbers ranging from 0,36 to 0.87 € per km[†], with a mean of 0.53 €. In the reference scenario used by the national transport authority, the running cost is the calculated marginal cost, 0,19 €. The assumption used in private car case is 0,19 € and for the shared car case 0,48 € for total cost per km, to account for fixed costs.

3.5. Driver's license

The parameter "Driver's license" determines which travelers can use a car. Since the assumption in this paper is that cars have achieved full self-driving capabilities this parameter is set to 100% to simulate that all travelers have the car as an alternative.

3.6. Car ownership

In the Shared cars case it is assumed that all travelers have access to a car in the form of a taxi service. To simulate this in the Sampers model car ownership was set to 100%. The availability of cars is an exogenous factor in the model, assumed to be determined by purchasing cost compared to income but, as described in Section 3.4, in the shared cars case the running cost has been increased and includes both running and fixed costs.

3.7. Headway for public transport

Bösch et al. (2018) estimates that out of the total cost for operating a bus, the bus driver constitutes around 55 %. The same number for train traffic is estimated to 4.7%. Eriksson et al. (2017) estimates the personnel cost to 55 % for bus and 18 % for train.

Stockholm PTA estimates that for bus traffic around 50 % of the cost is attributable to the driver but less than 5 % of the cost of the train is due to onboard personnel (driver, conductor and train hosts). However, outside peak traffic, the onboard personnel share of total cost for train traffic increases to somewhere around 40-60 % depending on the mode (less for high capacity trains, higher for trams).

These numbers indicate that there is a potential for doubling the service for bus traffic with the same cost as today, and doubling the service for train traffic outside of peak hours. Thus, in this paper it is assumed that the headway for bus traffic is halved for all times of the day and for train traffic halved outside of peak hours.

[†] Derived from table 2 in Wadud (2017) using 1 € = 1.1 £

3.8. On-demand public transport service

Pernestål Brenden and Kottenhoff (2018) describe six different types of new possible usage for self-driving buses in public transport made feasible by the lower operational costs compared to manually driven busses. Out of these, four describes door-to-door services and/or local trips in places where public transport is not available today due to either low benefit/cost ratio or physical limitations (e.g. a small street where a full size bus cannot turn today). The main benefit for travelers would be a service with more convenient and faster travel, connecting people to major bus stops or train stations.

For the on-demand PT system simulated in this paper, it is assumed that all bus lines with a headway of more than 10 minutes are eliminated and replaced with an on-demand service in all but the central parts. The service is estimated to have a mean speed of 25 km/h, including wait time for the service, and connects to all stops nearby with high-capacity public transport. Transfer time from public transport to the on-demand service is assumed to be effortless. The remaining bus and train lines have their headway decreased as described in 3.7.

Table 1. Summary of parameters as explained in sections 3.1-3.8. Note that the parameters are divided under the two dimensions, and combined into the four scenarios seen in Figure 1.

Car			
	Private car	**Shared car**	**References**
Value of Travel Time	Unchanged	Unchanged	(Le Vine et al., 2015; Milakis et al., 2017; Singleton, 2019; Soteropoulos et al., 2019)
Capacity on highways	Increased	Increased	(Friedrich et al., 2018; Milakis et al., 2017; Soteropoulos et al., 2019; Ye and Yamamoto, 2018)
Capacity on local roads	Unchanged	Unchanged	(Le Vine et al., 2015; Milakis et al., 2017)
Running cost	Unchanged (2 SEK/km)	5 SEK/km	Stjerna (2019), Wadud (2017)
Driver's license	100 %	100 %	Assumption
Car ownership	Unchanged	100 %	Assumption
Public transport			
	Conventional PT	**On-demand PT**	**References**
Headway for public transport	Doubled for bus. Doubled for train outside of peak	Doubled for lines with headway <=10 minutes	(Bösch et al., 2018; Eriksson et al., 2017)
Bus feeding system	-	All lines with headway over 10 minutes removed. Auxiliary trips from all zones to closest active stops set to 25 km/h.	Pernestål Brenden and Kottenhoff (2018)

4. Results

In this section, the major results from the scenarios are described and compared to the reference scenario.

4.1. Modal share

As can be seen in **Errore. L'origine riferimento non è stata trovata.**, the introduction of privately owned self-driving cars changed the modal share for cars from 38 % of all trips in the reference scenario to approximately 41 % in the scenarios with a private cars. In the shared car scenarios, 60 % of all trips were made by car.

The number of walking trips decreased by 4 % in both scenarios with private cars, and about 0 % for bicycling and public transport. For the scenarios with shared vehicles, the drop was greater, with the number of public transport trips decreasing with 32 %, bicycling decreasing with 30 % and walking decreasing with 26 %.

4.2. Changes in person kilometers traveled (PKT)

In contrast to the changes in modal share, the changes in PKT had bigger differences between the scenarios with private cars versus with shared cars, see Figure 1.

Total PKT increased in both scenarios with private cars. In these scenarios, PKT increased for public transport travel as well, but not as much as the service level. The introduction of an on-demand bus service increased PKT for public transport by 10 %. For walking and bicycling, the changes in PKT were small, less than -4 % in both scenarios with private cars.

In the scenarios with shared cars, the changes where larger. Travelling with public transport, walking and bicycling went down by 27, 31 and 32 % respectively in Conventional PT – Shared car and by 21, 30 and 31% for On-demand PT – Shared car. These trips were instead done by car. There was also a shift from longer trips to shorter trips with car, see Figure 2.

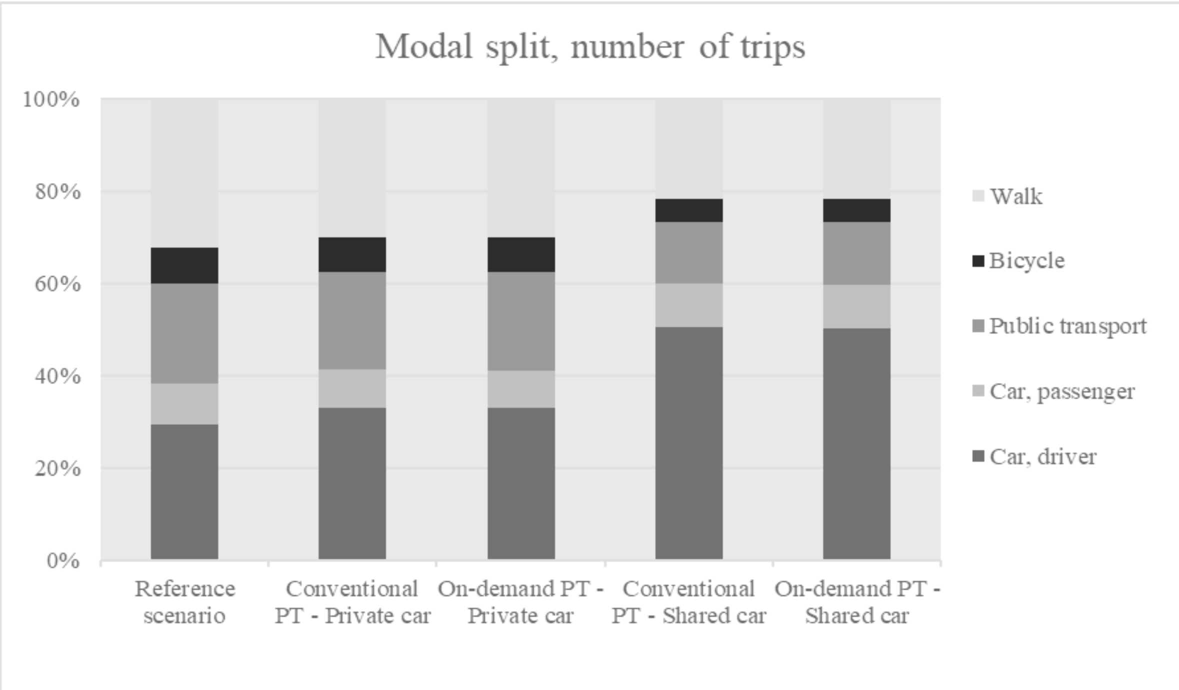

Figure 3. Modal split based on number of trips for each scenario.

PKT for the "car, driver" in Figure 1 can be directly translated to vehicle kilometers traveled (VKT). VKT increased by 15 % for the scenarios with Private cars, and by 8 % for scenarios with Shared cars.

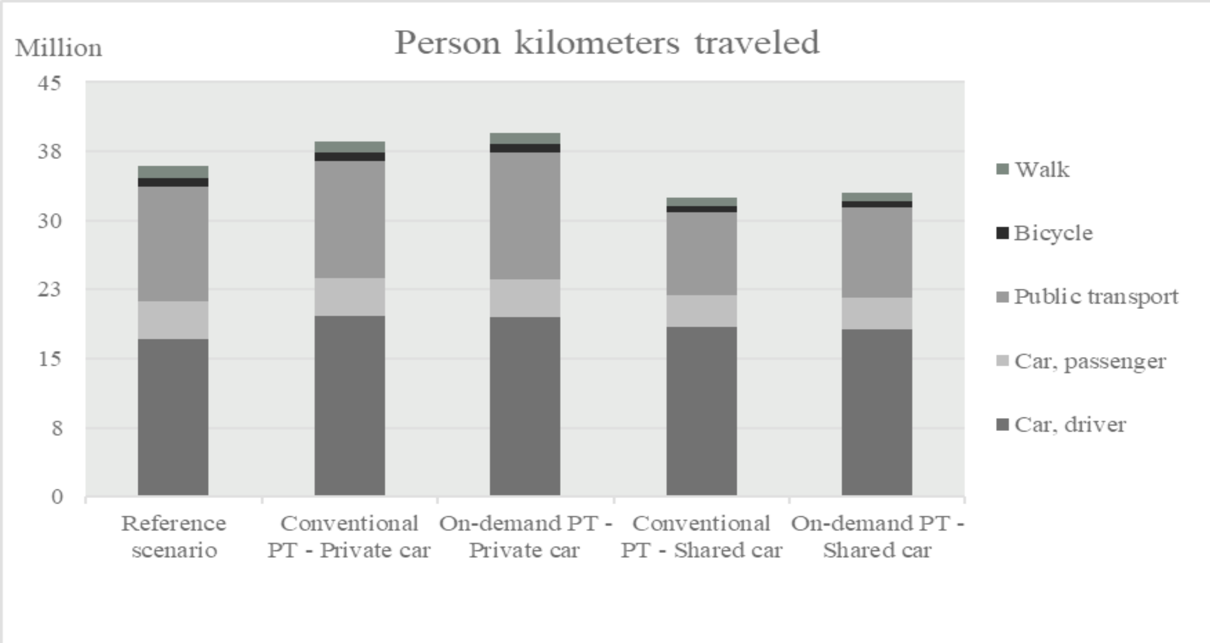

Figure 1. Person kilometers traveled for each scenario. Note that person kilometers traveled for "car, driver" can be directly translated to vehicle kilometers traveled for the car mode

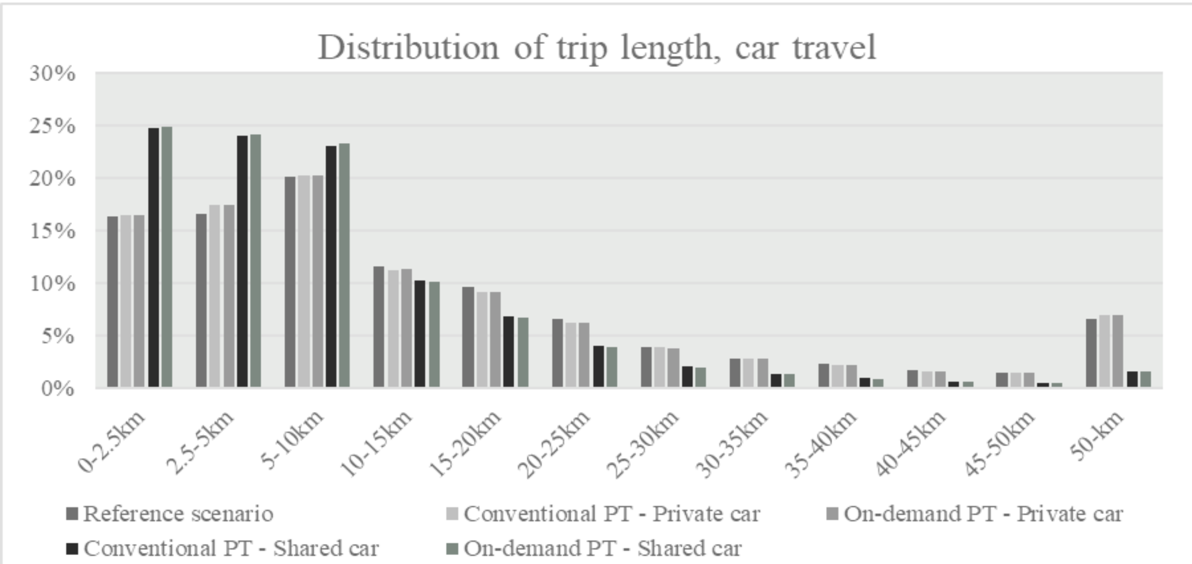

Figure 2. Distribution of travel length, car travel.

4.3. Changes in public transport travelling

The differences in public transport ridership were small between the reference scenario and Conventional PT – Private car and On-demand PT – Private car. In the scenarios with shared cars, there are significant decreases in PT ridership. However, in the city center public transport remained the dominating mode even though ridership fell.

The difference between the scenarios with Conventional PT compared to On-demand PT were marginal. However, the geographic distribution of the results of the on-demand service were unevenly distributed and it is possible that better solutions can be made.

5. Discussion

In this paper, four different scenarios explored potential development for public transport and the car. Several studies point to the possibilities of sharing vehicles (e.g. Meyer et al., 2017, Richter, 2018, or Zhao and Kockelman, 2018), especially the potential to reduce vehicle fleet size, but with the drawback of increased VKT, congestion and pollution. Zhao and Kockelman (2018) foresee an increase of VKT by at least 20% and a decreased bus traveling and Lu et al. (2018) an increase of VKT by at least 33%. The scenarios with private cars in this study indicate an increase of VKT by 8 % and the scenarios with shared cars an increase of 15 %, both numbers significantly lower. This likely might be due to different costs per kilometer are used in this paper compared to the previous studies. As Liu et al. (2017) points out, results are heavily dependent on the cost per kilometer. Comparatively, Bösch et al. (2018) show that shared cars might not necessarily be the option that is considered "cheapest" by consumers, as few people today incorporate the fixed cost into their perceived cost of travel.

Richter (2018) made a similar study as this one and found comparable results, with a decrease in active modes and small increase in public transport travel in some scenarios. In other scenarios, public transport significantly decreased on a regional level. Many shorter trips were made by taxi services but as he points out, it is plausible to expect that such a service would have a "start" cost to account for rerouting of cars, pick up time and transaction costs, similar to today's taxi services. It is therefore likely that increase of shorter car is overestimated and that the decrease in active modes would not be quite as big as indicated by the results in this study.

The extent of the effect from self-driving technology is likely dependent on geographic, cultural and technological conditions. However, the general direction might still be relevant and an increased service and accessibility level for both the car and public transport mode should mean less walking and bicycling. Even though car travel increased in the simulations public transport remained the main mode for travel in the central, denser regions of Stockholm, which points to public transport's spatial efficiency.

In this study, some aspects of essence to understanding the full impact have not been included, e.g. car relocating, changes in the value of travel time or trip sharing. The relocation effect may increase congestion in the road network, thereby decreasing the total demand for travel by car and also increase VKT. The value of time likely increases the attractiveness for car travel. Trip sharing, i.e. several people sharing a car and thereby reducing the cost per kilometer, has not been examined either. All these factors would likely impact results significantly and should be examined further. As has been pointed out by numerous papers, the results from these types of studies are heavily dependent on assumptions of parameters.

6. Conclusions

In this paper four different scenarios with self-driving mobility services were implemented in Stockholm, Sweden. The evaluation has been done with Sampers, the Swedish national transport model.

The increased service level in public transport is shown to have a relatively small impact on travel demand. In contrast, transitioning from a privately owned car to a taxi-like service led to significant decreases for public transport, walking and bicycling. However car travel seems to be dependent on assumptions of cost per km as confirmed by previous studies. The increase of car travel was great, but public transport remained the dominating mode in denser parts of the city, owning to greater capacity.

The results indicate large differences of impacts based on assumptions of how self-driving technology will be used. This raises the need for urban planning to take a dynamic approach and use e.g. sensitivity analysis and scenario planning to assess impacts given different future developments.

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