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Self-driving shuttles as a complement to public transport – a characterization and classification

Anna Pernestål Breden a*, Karl Kottenhof b

[a]*Integrated Transport Research Lab, KTH Royal Institute of Technology, 100 44 Stockholm, Sweden*
[b] *Traffic planning, Economy and Engineering, KTH Royal Institute of Technology, 100 44 Stockholm, Sweden*

Abstract

Sustainable transportation is a top priority challenge for many cities and urban regions. To reach that, an attractive public transport plays a key role. In this paper an analysis of how the technology of self-driving vehicles, and in particular shuttles for about 6-20 passengers, can complement and improve attractively in public transport. Self-driving shuttles provide a new component to public transport, as smaller vehicles can operate on a higher frequency to a cost of the same order of magnitude as conventional larger buses. Six types of applications of self-driving shuttles in public transport are identified: Feeder line, Truncation of high capacity line, Cross connections, Center line, On-demand feeder line, and Within-area service (line or on demand). The application types are exemplified by two potential cases in Stockholm, and implementation barriers and strategies are discussed. The classification, together with examples from on-going applications, suggests that SD shuttles can contribute to public transport already without being fully self-driving everywhere.

Keywords: Self-driving vehicles; autonomous vehicles; public transport; shuttle;

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* Corresponding author. Tel.: +46-73-756-2443; fax: +46-8-790-6500.
E-mail address: pernestal@kth.se

1. Introduction

Sustainable transportation is a top priority challenge for many cities and urban regions. Public transportation together with other shared mobility modes, such as car and ride sharing, are crucial to achieve sustainable city transportation that also provides an effective use of the space in the cities. In this light, the ongoing development of self-driving vehicles is interesting and relevant, as self-driving vehicles has the potential to improve public transportation, e.g. by providing first/last mile services (Alessandrini et al., 2014; Pernestål Brenden et al., 2017).

Development of self-driving (road) vehicles (SDVs), also referred to as autonomous or fully automated, is fast. SDVs are currently entering public streets in various pilots and tests. SDVs, i.e. vehicles of SAE level 4 and 5 (SAE International, 2016), promise a fundamental change in mobility, and are expected to have an impact on living and transportation (Fagnant and Kockelman, 2015; Meyer et al., 2017; Milakis et al., 2017).

In the literature on the impacts and potential applications of automated road vehicles, there is a clear bias towards evaluation of the different applications based on autonomous taxis. Simulation studies investigate their potential to match services of personal cars (Burghout et al., 2015; LaMondia et al., 2016; Meyer et al., 2017) or replacing conventional public transportation (Merlin, 2017). The autonomous taxi application raises two sustainability challenges. First, the total amount of vehicle kilometres travelled (VKT) will increase due to empty vehicles repositioning (Burghout et al., 2015; OECD International Transport Forum, 2015) as well as due to an increased travel demand caused by both lower travel costs and new mobility options for children, elderly and the disabled (Anderson et al., 2014; Brown et al., 2014; Burns, 2013; Fagnant and Kockelman, 2015). Increased VKT leads to an increase in the number of vehicles driving on the streets, and increased energy consumption. Second, as autonomous taxis are expected to provide a service that is more attractive than conventional public transport, but to a cost lower than the one for manually driven taxis and private cars (Fagnant and Kockelman, 2015), modal shifts from high capacity public transport to the autonomous taxi services can be expected.

To obtain a sustainable transportation solution, with reduced VKT and energy consumption, the use of self-driving vehicle as a complement to public transport is a key (Alessandrini et al., 2014; OECD International Transport Forum, 2015; Pernestål Brenden et al., 2017). Yet, systems where self-driving vehicles complement high capacity public transport are still not well studied. This paper target this gap by increasing the knowledge about how such systems can be designed to meet the transportation challenges of cities and urban regions.

In this paper, the term “public transport” includes publicly funded/operated transportation as well as commercial mass transit offers, including high capacity transportation (buses, trains, metro, tram, but not taxi). The technology for automated transit rail systems are already well established (Malla, R, 2014), and will not be considered in this paper. Instead, the focus is on the application automated road vehicles, and in particular self-driving shuttles (SD shuttles), i.e. small buses carrying 6-20 passengers on roads. This application is chosen since it adds a new component to the traditional public transport system. Automation of large buses is an interesting option, but this is also omitted in this paper. In the paper, the term SDV will be used to refer to self-driving vehicles in general, and the term SD shuttles will be used to refer to the small buses in particular.

The paper contributes with a first analysis of how self-driving mini buses shuttles can be used to complement public transport, including a literature survey, an analysis of the characteristics and a classification of SD shuttles and how they meet the challenges of public transportation, a discussion on implementation barriers and a recommendation for future work. By performing the analysis on how SDVs can complement and improve public transport already now, when the first self-driving systems still are under development, is beneficiary from three perspectives. First, it gives the possibility to affect the development in a direction that is beneficiary for the application as complement to public transportation. Second, investments in infrastructure may be needed – such investments typically take long time. Third, to obtain a sustainable transportation system where SDVs contribute, decisions may be needed by city planners and policy makers. If they are not taken on correct basis there is a risk that the development goes in a not so good direction.

2. Methodology

The results presented in the paper consist of three parts: a literature review, an analysis of the characteristics of SD shuttles in relation to public transport, and a classification of SD shuttle applications. The literature review is based on articles found via Scopus and Primo search tools, by using the keyword public transportation / transit in combination with any of the following keywords: automated (road) vehicle(s), automated road transportation, autonomous vehicle(s), self-driving vehicle(s). Relevant references in the articles found where also used. Since the search result was limited, also Google and Google Scholar were used to identify more recent or unpublished studies. An analysis and a classification of self-driving vehicles as complement to public transport is based on the authors' professional public transport experience and analytical reasoning, with input from studies and visits of ongoing pilots with self-driving shuttles and other automated applications as well as several interviews with different stakeholders (see Appendix A). The interviewees included suppliers of self-driving shuttles, public transportation operators, operators of shuttle services, public transport authorities, and researchers. The interviewees came from five different European countries. Interviews and study visits were performed during 2016 and 2017.

3. Literature review

Literature on use cases for self-driving vehicles is heavily biased towards transportation systems based on (shared) autonomous taxis, and their performance as an alternative to private car usage (Burghout et al., 2015; Chen and Kockelman, 2016; Gruel and Stanford, 2016; Meyer et al., 2017; OECD International Transport Forum, 2015), or routing strategies for such systems (Han et al., 2016; Suganuma and Yamamoto, 2016). Literature on self-driving vehicles in public transport is much sparser, and provides primarily two types of applications: complete systems of smaller self-driving vehicles that replace existing public transportation and first/last mile transportation services e.g. between a public transportation hub and a business area.

The systems with automated road vehicles replacing public transport operate either in a railway-like manner with smaller vehicles in platoons (Blumenfeld et al., 2016) or in a taxi-like manner covering a city or larger area (Lam et al., 2016; Meyer et al., 2017; Ponsford and Kunur, 2006; Suganuma and Yamamoto, 2016). The systems are expected to increase accessibility for the traveler, especially in medium sized cities. However, the impact on energy consumption, utilization of city space, and other societal aspects are not yet thoroughly investigated for these solutions. Merlin (2017) show that, when replacing a conventional bus system with shared autonomous taxis it is theoretically possible to reach the same level of greenhouse gas emissions, but as VKT increases with a factor between 5-12 the energy consumption of the single vehicles is an important factor for the total emissions of the system. Furthermore, simulations show that the total amount of vehicle kilometers driven (VKT), and thereby the energy consumption and the amount of vehicles occupying the streets, may increase rather decrease when comparing systems of autonomous taxis with today's private car usage (Burghout et al., 2015; OECD International Transport Forum, 2015). Although road capacity is expected to increase with SDV, the increase in VKT caused by systems of autonomous taxis, leads to congestion challenges and reduces accessibility in cities (Meyer et al., 2017).

The report by OECD International Transport Forum (2015) shows in simulations that a combination of autonomous taxis and public transport can reduce the number of vehicles with 90%, but VKT increases with 6%. In an alternative scenario, where only autonomous taxis are used, gives an increase in VKT of 89%. Furthermore, the potential accessibility, economical and usability benefits of these systems will be realized when vehicles are self-driving everywhere (or at least in most places) and the systems are fully implemented (Litman, 2017; OECD International Transport Forum, 2015). However, even if self-driving vehicles are currently entering public streets, reaching this point is still predicted to be 20-40 years from now (Litman, 2017).

Alessandrini et al. (2014) mean that self-driving vehicles are best used in systems, called Automated Road Transportation Systems (ARTS), where vehicles are interlinked via information systems. They list four different types of ARTS; Personal Rapid Transit (similar to the systems with autonomous taxis), Cyber Cars (similar to shared autonomous taxis), High Tech Bus (to be used in high capacity links), and Dual-mode Vehicles (manually driven low-emission cars supported by advanced driving systems such as automated parking). ARTS can operate on exclusive or shared lanes.

There is almost no literature targeting how self-driving vehicles can complement existing public transportation. First/last mile applications and low demand / off-peak traffic are sometimes mentioned as examples but without further details on the implementation. In the EU project Citymobil2, demonstrations using shuttles were set up in several European cities to show the concept of shuttles, but to provide a fully usable and attractive service further steps, both in technology, business and systems are needed (Citymobil2 consortium, 2016).

Stated preference investigations on users' interest in using self-driving vehicles in first/last mile services show that in general, users are not attracted by the fact that the vehicles are self-driving (A. Alessandrini et al., 2014; Menno D. Yap et al., 2016). Instead, focus should be on providing a relevant service.

4. Characteristics of SDV in public transport

4.1. Challenges in public transport

Two of the main challenges within public transport are: increased costs, and to provide sufficient service in areas with lower travel demand (Eriksson et al., 2017; Holmgren, 2013; RAC, 2017). Many cities are sprawled over large areas with sub-urban regions with low density of residents living in villas or industry areas. Public transportation in those areas typically has low frequency, and the walking distance to stations and bus stops are often long. This gives a public transport system that is not attractive to all residents. Yet another challenge is to provide efficient cross-connections between suburbs. In practice, this means that it is challenging for public transport to provide sufficiently high frequency to be an attractive alternative to the private car.

4.2. Main characteristics of SDV in public transport

For buses operating in public transport in Sweden, typically over 50% of the operational costs are related to driver salaries (Eriksson et al., 2017). Thus, if the driver can be removed by using SDVs, the operational costs per vehicle can be reduced dramatically. This opens up for two new main possibilities:

- Reducing operational costs by operating the same public transport system, i.e. using the same number and size of vehicles but operate them without drivers.
- Keep operational costs at the same level while improving the service, i.e. using several, smaller vehicles to increase flexibility and/or area of operation.

4.3. Technological aspects of SDV for public transport

Vuchic (2007) classifies public transport modes according to three dimensions, Separation from other traffic, Technology, and Traffic/operation, see the first column of Table 1. The separation dimension includes the degree of right of way (ROW) in relation to other traffic modes. The technology dimension relates to vertical support, lateral steering, propulsion, and control and speed. Finally, the Traffic / operation dimension relates to size of the transport system, type of traffic and the type of service offered. These dimensions are relevant also for understanding new types of vehicles and transportation modes, and comments on the three dimensions for SD shuttles in public transport are given below and in Table 1.

Table 1. Three dimensions for classification of public transport (simplification of Vuchic (2007)), and their application to SDV (shuttles).

Dimension	**Alternatives**	**Comments for shuttles (SDV) in public transport**
Separation from other traffic	Exclusive track, Prioritized, Normal road (mixed traffic)	Currently, shuttles typically operate on a pre-programmed route, like a track, but without an exclusive right-of-way. This adds a new alternative for the separation dimension.
Technology, including (1) Support, (2) Guidance//Positioning (3) Propulsion, (4) Control and speed	(1) Asphalt, concrete, rail, single rail (2) Magnets, GPS, Camera, Lidar, Radar (3) ICE, hybrid, electric (4) Driver – automatic	The SD shuttles considered here are small vehicles that run on asphalt or concrete roadways. They can be guided by a combination of electronic maps, detection electronics, and GPS. The propulsion is electric and all is supervised by an obstacle detection system.
Traffic / operation (1) Line length (2) Type of operation (3) Trips served	(1) Local, regional. part of network (2) Feeder traffic (last mile), city traffic, within major facility/area etc. (3) Commuting, recreation, tourist	Operation on the "Last Mile" is often mentioned for small SDVs. Several such types of operation is described later in this paper.

Operational speed for both manually driven buses and SD shuttles is correlated with the degree of separation from other traffic. In fact, it is typically an even larger challenge for SD shuttles than for conventional buses since SDVs are programed to have a conservative way of operate to avoid accidents. Thus, SDVs tend to adjust their speed to the slowest road user (Citymobil2 consortium, 2016), which means that driving in mixed traffic, especially at the same roads as pedestrians, will lead to very low operational speeds. Although the SD shuttles handle mixed traffic, a prioritized or exclusive track will provide higher operational speed and thereby a better service. Low operational speeds limit applications to local or first/last mile applications. If separated runways (roads, lanes, tracks) are used speed and regularity will increase. In the future even high speed Bus Rapid Transit applications (BRT) can be considered.

In the public transport use case, SD shuttles will typically operate within limited areas or on predefined tracks, at least in the early application stages. Therefore, the need for operation “everywhere” is less critical, and it may be an attractive alternative to adjust the infrastructure (i.e. by using an electronic track and some barriers to protect from other traffic and to improve the system performance. A benefit of electrified propulsion is that vehicles can also operate inside e.g. hospitals or shopping malls.

4.4. Other aspects of SDV in public transport

The information in this section is primarily based on input from interviews with key stake holders and experts within self-driving vehicles and public transportation. Most interviews where performed during the autumn 2016, and involved business experts and technical experts from two suppliers of automated vehicles for public transport, project managers for pilots with self-driving shuttles, public transportation strategists, business developers at public transport operator, and researchers within public transportation.

Costs: Compared to manually operated vehicles, the operational cost per SDV decreases significantly. On the other hand, the fixed price per vehicle (of a certain size) increases due to the SDV technology.

Capacity: The same theoretical capacity (passengers per hour) can be obtained by using several smaller vehicles and fewer larger. The removal of the driver, and thereby the operational costs per vehicle related to that, opens up for the possibility to choose the type of operation that is best suited for the application (depending on travel demand and network design.) Often lower capacity is needed at the outer parts of the lines, where often the buildings are more sprawled. This can be solved by smaller but more vehicles at the end of (truncated) trunk lines.

Maintenance & Repair: Maintenance and repair is a part of operational costs for public transport vehicles. Self-driving vehicles in public transportation are expected to reduce repair costs, by supporting maneuvering in places with limited space and avoiding accidents. Another effect of self-driving vehicles is a decreased need for space at terminals and garages: smaller vehicles are easier to handle, self-driving vehicles can park themselves in a more efficient way. On the other, experiences from para-transit vehicles in developing countries show that a larger number of vehicles may need more space in terminals and garages.

Network design: Ultimately, public transportation should provide two services that are contradictory: the stops (or “pick-up points”, should be close to the activities (home, work/school, shops, etc), but public transportation should also provide a fast means of transportation between activities (reduce travel time) (Nielsen, 2005). To service a large area, public transportation is typically outlaid as lines going through the city center. This an effective design for high capacity lines and high productivity, but it makes travel between neighboring regions time consuming as the passenger needs to go into the city center and then out again.

Operation: Self-driving vehicles are expected to affect the operation in a number for ways. The most interesting aspects from an operation point of view are:

- Regularity in operation due to automatic control of e.g. speed.
- Utilization of vehicles since breaks (regulated driver resting times) and changes of driver are not needed to take into account. On the other hand, battery charging may limit the availability of the vehicles.
- Implementation of on-demand operation as vehicles are connected to a central traffic control system, where on-demand can be implemented as a function.
- New possibilities to provide flexible routing (if implemented in the traffic control system).

Security: One challenge with driver-less vehicles in public transportation is that the driver is not only a driver, but also a steward that provides information and support, and a supervisor that prohibits unsecure situations. The tasks below need to be resolved in other ways, for example by using supervision systems, artificial intelligence, remote operators etc.

- Increased uncertainty for passengers in the absence of a driver – no one can help and guide the passengers. This may especially be an issue for elderly that need help or for persons with less experience of public transport.
- Decreased security (in relation to other passengers). Can potentially be a larger problem for women (on the other hand women are more frequent users of public transport and gain benefits since the service level increases).

5. SDV applications in public transport

5.1. Classification of SD shuttle services

As SD shuttles make it feasible from a cost perspective to operate buses of smaller size than traditional buses they introduce a new component to public transportation. Utilizing this new component, and addressing the challenges within traditional public transport systems described in Section 4.1 six types of application of SD shuttles were identified: feeder line, truncation of high capacity line, cross connections, center line, on-demand feeder line, and within-area service (line or on demand). The application types are described in Table 2, and schematic pictures of them are shown in Figure 1.

The applications a), d), e) and f) have been tested or are in operation in different places today, for example in Netherlands (2GetThere, 2017) and Switzerland (A-M. Brouet, 2016). The applications b), truncation of a high capacity line, and c), cross connections, are to the author's knowledge not yet tested. These two are especially interesting to make public transport networks more efficient and attractive.

Table 2. Description of the SD shuttle applications and the public transport challenges they address. The letters in the first column refer to the subfigures in Figure 1.

Fig no	**SD shuttle application**	**Challenge addressed**	**Description**
a)	Feeder line	The distance from/to activities to high capacity public transport is too long.	SD shuttles as feeders to and from high capacity public transportation hubs or stations.
b)	Truncation of high capacity line	The costs of operating public transport in low demand areas (typically in the ends of high capacity lines) is high (most passengers uses the middle part of the line).	Replace the end parts of the high capacity line with SD shuttles that are timed with the high capacity line. This will free up time on the larger vehicles that makes it possible to increase frequency of the high capacity line. SD shuttles can be used to service a larger area to the same cost of a large bus (this also gives a feeder functionality).
c)	Cross connections	High capacity lines are typically spread in distance and provide links from a city center out to suburban regions. Attractive cross-connections need frequent service but this is costly.	SD shuttles can provide connections, or short-cuts, between main lines. This gives a "network-effect" that decreases travel times in the network.
d)	Center line	City centers are often crowded, and have narrow streets that are not suitable for large buses. Furthermore, traditional public transport can be less useful for transportation within the city center / area	The center line provides a local line within a e.g. a city centrum, and provides means to avoid large buses in the crowded areas. In this application, the high capacity public transport lines can also serve parking lots.
e)	On-demand feeder line	The high capacity public transport is to coarse to give short walking distances for potential customers all and ordinary bus feeders give low quality service.	The SD shuttles provides on-demand feeder to/from the high capacity public transport. This solution is particularly interesting where ordinary feeder buses have low quality.
f)	Line or on-demand service within an area	Many stops or potential pick-up points in an area makes the traditional public transport lines slow. This gives long waiting and travel times and poor cost efficiency.	Bus services can be on-demand but SD shuttles also enables on-demand service, without operating on specified lines. This provides a lot of flexibility, and can complement or replace traditional public transport, where demand is limited or during off-peak hours in cities.

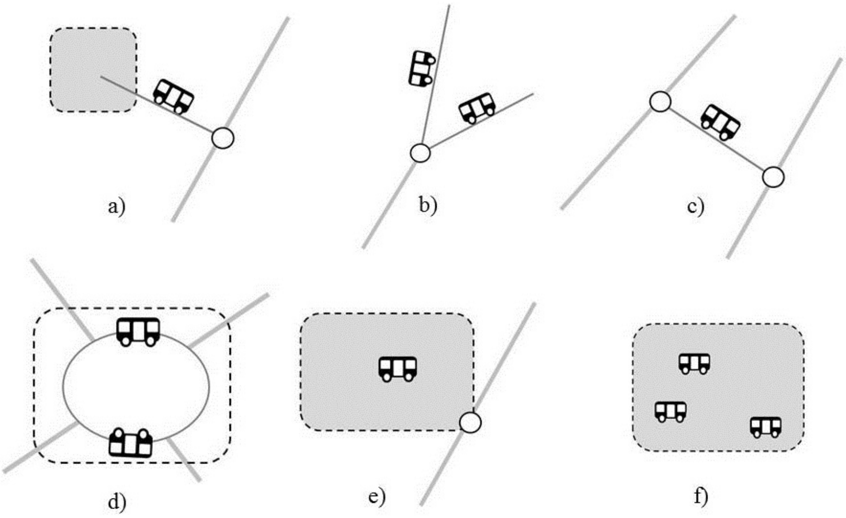

Figure 1. Types of operation of SD shuttles as complement to public transport: a) feeder line, b) truncation of high capacity line, c) cross connections, d) center line, e) on-demand feeder line, and f) within-area service (line or on demand).

5.2. Examples of new applications in Stockholm

To provide concrete examples of new applications of SD shuttles to complement public transport, two potential applications in Stockholm are studied: a business park and a residential area are presented in Table 3. For both applications, a first set of simulations of the new services have been done in using the simulation tool VISUM (PTV, 2017) and provides early indications on the impacts of the suggested SD shuttle services.

Table 3. Two potential applications in Stockholm to exemplify the classification of SD shuttles in public transport

Name of site	**The business park (Kista)**	**The residential area (Örsvängen)**
Site description	A business park is placed between a metro station and a commuting train station. The distance between the two stations is approx. 2 km. A bus connects the two stations as a part of a longer route, and by taking a detour	An approx.1,5 km long loop within an residential area, connecting the residential area with a local centrum with a metro station. The route is currently operated as the last part of line with a large bus having the frequency of four buses per hour.
Challenge	The metro and the train station have uncorrelated cross connections. Also, the business park needs a feeder service.	The demand in the area is relatively low since people without special needs (or a lot of luggage) can walk the distance. Operating the large bus is costly for such a low demand. In addition, the low frequency makes the service unattractive.
Suggested SD shuttle application	a) Feeder line, c) Cross connection, f) Within-area service	a) Feeder line, b) Truncated line
Impacts of SD shuttles	The simulations show that SD shuttle users differ from the bus users in two ways. First, for the bus users the distance between the stations is part of a longer route, while the SDV users travel mostly within the business part. Second, travelers within the business park seem to prefer higher frequency and lower speed, while travelers through the business park prefer higher speed and synchronization with the rail lines.	The simulations show that by replacing the existing bus with two SD shuttles operating with a frequency of 15 departures per hour, the number of passengers will increase with 180%. For costs of similar magnitude (i.e. using the assumption that the costs of operating the SDVs will be of the same order of magnitude as the big buses), more passengers will use the public transportation

6. Discussion on implementation challenges and strategies

As described in Sections 4 and 5 SD shuttles provide several possibilities for improved public transport services. However, there are also a number of challenges. In this section implementation challenges and opportunities are discussed.

6.1. Implementation challenges

Integration with existing public transport - Most of the applications of SD shuttles described here introduces a change between two modes of transportation, for example as feeder lines to high capacity public transportation. This is one of the keys for creating an effective transportation system where high capacity modes are complemented in areas with lower demand. However, to be successful, these changes between transportation modes need to be friction free, and the SD shuttles need to be integrated with the public transport in four different ways. 1) Physical integration at bus stops and stations for smooth change-over. 2) Timing of arrivals and departures. 3) The ticketing system must be smooth and integrated (even if the SDV service is run by other operators than public transport). 4) Integrated on an information level, so that information of routes, disturbances etc. flow in a transparent way.

Low operational speed in mixed traffic - Today, and most likely for several years from now on, the SD shuttles in mixed traffic will operate with low speed and in a conservative manner to avoid any accidents. SD shuttles will also run into situations, which they do not resolve by themselves, and thereby stop and become standing still. This is not acceptable in a transportation service, and needs to be resolved. One solution, which will probably be used in self-driving cars, is to have a responsible person on-board that can take over and guide the vehicle around obstacles etc. For SD shuttles in public transport, this is not an attractive solution, as one of the main drivers for introducing the SD shuttles is to reduce operational costs caused by the driver. An alternative solution is to have a remote operator that can be in charge of a whole fleet of SD shuttles, and guide the vehicles remotely (Bout et al., 2017). This solution requires that the vehicles can operate safe by them self, while the remote operator take control over the vehicles primarily to provide a high enough operational speed.

Changed business models - SD shuttles without on-board staff changes the cost model of public transport operation, as it provides lower operational costs to the cost of higher investment costs (at least in the beginning). Furthermore, investments in changes in infrastructure may be needed. This challenges the business models of public transport: Who should make what investments? Especially in cases where operation contract times are limited. This new cost model contradicts existing models, and new incentives for public transport operators may be needed to take use of the new technology. Also new types of contracts may be needed. Another scenario is that the SDV vehicles are operated in new constellations of public-private partnerships (Pernestål Brenden et al., 2017). Besides business models, this may also challenge regulations related to subsidies.

Competition with new mobility services - Self-driving technology opens for new types of mobility services, for example autonomous taxis that are expected to provide taxi-like services to costs that are significantly lower than traditional taxi services (Chen and Kockelman, 2016; Meyer et al., 2017; OECD International Transport Forum, 2015). If these types of services are successfully developed they may become a threat to public transport's scale advantage for high productivity.

6.2. Implementation strategies

The benefits of using SD shuttles as a complement to public transport depend on how the application is set up, and it is possible to obtain effective and attractive services also if SD shuttles are not fully self-driving everywhere (i.e. before they are SAE level 5).

The two examples Rivium Park Shuttle (2GetThere, 2017) and Sion SmartShuttle (A-M. Brouet, 2016; Michel, 2017) illustrate two different levels of complexity in the implementation. The Rivium SD shuttles operate on a protected track. Yet they are a feeder line (type a) in Table 2), and successfully feeds the high capacity public transport network since many years. In Sion the vehicles are operated in mixed traffic environment with a lot of disturbances, and a low number of passengers benefit from the service. The costs are high due to the low speed and two onboard personal for safety reasons. As suggested from those two examples, it can be valuable to implement solutions at lower steps to obtain services that actually provide user benefits. At the same time, tests at higher steps are important to develop and verify new technology.

There are several reasons for using a stepwise introduction of SD shuttles as a complement to public transport. First, technology and also legal framework will develop fast. Second, to continue to be an attractive mode of transportation public transport should not stay behind the development of self-driving cars and taxis. Third, starting with the development now will provide continuous experiences for a wider use of SD shuttles in public transport, with respect to technology, user aspects, and implementation and operation costs. This motivates a stepwise implementation were the SD shuttles first are operated in applications of different levels of complexity. The first level is operation in a protected area without conflicts with other traffic. Later the operational environment is made increasingly more challenging with interactions with other road users. For each of those steps user values and security of the service, as well as costs for vehicles, infrastructure and operation should be evaluated. This strategy is valid for all the operational types described in Table 2. By considering different operational types, a less complex environment, or by means of a remote operator that can guide the vehicle through complex situations, SD shuttles can provide an effective service already before they are fully self-driving.

7. Conclusions and future work

The paper has targeted the question on how self-driving vehicles can complement public transport. A literature review, visits at pilot test sites and interviews with experts within the field of self-driving vehicles and public transport have been performed and analyzed. Characteristics of SD shuttles as a complement to public transport and a classification of applications for SD shuttles have been described. Furthermore, implementation challenges and a stepwise strategy for implementation have been presented.

There is a bias in today’s research towards applications based on autonomous taxis providing on-demand services. Among public transport related services, mostly “first/last mile” is mentioned. The classification provided in this paper shows that the possibilities for SD shuttles in public transport is broader than that and need better definitions. The classification, together with examples from on-going applications, suggests that SD shuttles can contribute to public transport already without being fully self-driving everywhere.

The fact that there are a variety of applications of SD shuttles in public transport suggests technology should be developed and tested in the different applications. To fully understand the potential of SD shuttles as complement to public transport, future work should include both simulations of the different concepts as well as actual pilots. In particular, the investigations of the potential of the truncation of high capacity line (type b) and the cross connection (type c) is needed. Simulations should also include evaluation of different applications not only from a user/accessibility perspective but also from economic, environmental and societal perspectives.

Furthermore, as smooth integration between public transport and the SD shuttles is important to make the services attractive, future work should also include studies of this integration from different perspectives, including physical and information (data) aspects. The fact that there are a variety of applications of SD shuttles in public transport suggests technology should be developed and tested in the different applications. Adding SD shuttles as a complement to public transport is not about removing the driver from current operations, but adding a completely new component with other capabilities to the public transport.

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Appendix A. List of interviews

This publication is based on semi-structured interviews with the following experts: CTO, SD shuttle manufacturer (2016), Project manager, SD shuttle pilot (2016), Operator, SD shuttle pilot (2017), SD shuttle operators (2016, 2017), Business developer, Public transport operator (2016), Business developer, ITS supplier (2016), Researcher, Vehicle developer (2016).

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