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Lessons learned from setting up a demonstration site with autonomous shuttle operation – based on experience from three cities in Europe

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ABSTRACT

The interest in operating autonomous vehicles is growing and several demonstration sites using automated shuttles have been established all over the world. Major work is involved in setting up an automated shuttle operation that involves more than identifying the relevant site, including adhering to current regulations and obtaining approval, as well as a considerable amount of preparation and commissioning required at the site. The shuttle must pass relevant national vehicle regulations, and the operation site has to undergo a site assessment. This paper is based on lessons learned achieved from setting up automated shuttle operations in three different areas in Europe: Brussel (Belgium), Linköping (Sweden) and Turin (Italy). The focus is on the practical aspects of operation. Through the experience we have gained of setting up demonstration sites at three locations in Europe, we have identified the need to summarise the lessons learned from preparing AV shuttle operation sites in order to facilitate the implementation of other operation sites. Hence, this paper aims to consolidate lessons learned during preparation and implementation of automated shuttle operations in near urban environments and to identify the path toward future implementation The three sites operate different brands and number of shuttles, different types of infrastructure and varying local conditions. The focus here was on generic lessons learned and not to understand differences between brands and operators. It is clear that further development of the AV shuttles is vital to ensure that they operate smoothly in complex traffic situations considering lane and road width, shared spaces, snow, dust, rain, leaves, birds, etc. Adapting the road infrastructure to enable the shuttles to run in the autonomous mode should be avoided, instead the shuttle development should prioritise fitting into the existing traffic environment and eco system. Mitigation areas have been identified covering: road infrastructure, weather dependant operation, season dependent operation, improvement of localisation, digital infrastructure, design and working conditions, and citizens' user experience.

1. Introduction

The interest in operating autonomous vehicles is growing and several demonstration sites using automated shuttles have been established all over the world (Iclodean et al., 2020). The authors foresee a positive impact of these vehicles on public transportation once they have been rolled out large-scale. To date, the driving force for demonstration and operation with automated shuttles is primarily technical and innovation based (Skogsmo & Anund, 2021). The demand for an open, socially constructed process for automated vehicle (AV) development has become apparent and research must not only address the technical, but also the societal dimension of transitioning to AVs (Milakis & Müller, 2021). Oldbury and Isaksson (2021) point to a need to develop a more clearly articulated policy and planning agenda which clarifies the long-term public vision for automation in infrastructure and transport planning. Regarding governance arrangements around smart mobility solutions a tendency towards a transfer of roles has been observed, whereby bus operators will gain a new and influential role in smart mobility in public transport. This has created a need to think critically about the ways in which roles, relations and responsibilities may be shaped and reshaped

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in collaborative governance. Currently, the main findings about safety operators and barriers to autonomous vehicle adoption are synthesised in two recent literature reviews (Alawadhi et al., 2020; Bezai et al., 2021).

An issue often raised in relation to automation, is that users, the passengers as well as the safety operators, are generally not kept in the loop during the design and development of automated solutions in general (Anund et al., 2019). Studies often focus on user feedback of an existing service. A study of the user perspective in general in the Baltic Sea area showed that across all cities, the feedback from passengers is remarkably positive with regard to personal security and safety onboard (Bellone et al., 2021). In addition, the importance of safety operators was highly rated.

Despite the clear statement in the UN Sustainable Development Goal 11.2 (UN, 2021) about providing access to safe, affordable, accessible and sustainable transport systems the aim of automated operations is, to the best of our knowledge, in general not being developed as a mobility solution accessible and available for all. It can be seen in the literature that automated shuttle usage has been studied in relation to age, gender and income, but rarely in relation to user groups with special needs Zubin et al. (2020). Instead, Zubin et al. (2020) concludes that research gaps are found in infrastructure and network design as well as the topic of how to remove human personnel on automated shuttles. In a paper by Nesheli et al. (2021) more than 25 ongoing operations were reviewed and lessons learned were summarised. The paper was however not dealing with the operators' own perspective and insight into planning and solving daily issues to keep them up and running. Three key dimensions were focused looking at deployment locations, service characteristics of the shuttles, and stakeholders in 19 operations on going in US (Haque & Brakewood, 2020). The paper focus is on where they are up and running and the type of service they provide and what stakeholders that was involved or responsible for the operation. Lessons learned with focus on a stable operation it-self was not the main focus.

The most used classification system for automated driving that describes the role of the Human and the System in various levels of automation is the International Standard J3016. It covers the taxonomy and definition of terms related to Vehicle Automated Driving Systems ((SAE), 2016), and defines six steps from 0 (no driving automation) to 5 (full driving automation). Automated shuttles are generally on the SAE Level 4, which requires the presence of a physical legal responsible safety operator in charge of traffic safety like in normal vehicles, although the AVs mostly operate by themselves. In this paper, focus is on the SAE Level 4.

Setting up an automated shuttle operation is a major work that involves more than just identifying the relevant site. The set up also includes adhering to current regulations and obtaining approval, as well as a considerable amount of preparation and commissioning required at the site. The shuttle must pass relevant national vehicle regulations, and the pre-operation site must undergo a site assessment i.e., fulfil various criteria for the selection of a site. We have gained significant experience from setting up demonstration sites at three locations in Europe, and this paper summarises the lessons learned from preparing AV shuttle operation sites, to facilitate the implementation of other operation sites.

2. Aim

This paper aims to consolidate lessons learned during preparation and implementation of automated shuttle operations in near urban environments and to identify the path toward future implementation. The lessons learned were gained from setting up automated shuttle operations in three different areas in Europe: Brussel (Belgium), Linköping (Sweden) and Turin (Italy).

3. Background

The text below presents a description of the three demonstration sites. For the specific selection of driving site each environmental context undergoes a site assessment, carried out by the OEMs forming criteria and guidelines for a successful AV operation implementation. Thus, it is up to the client to either neglect or accept the necessary infrastructure requirements. An overview of the operational data of the different demonstration sites can be seen in Table 1.

3.1. Brussels

In 2018, Brussels Intercommunal Transport Company (French: Société des Transports Intercommunaux de Bruxelles (STIB)) decided to carry out a first test program of autonomous shuttles based on a one-year rental contract comprising two shuttles. These shuttles were deployed between 2019 and 2020 through a step-by-step approach based on 3 different consecutive demonstration sites in Brussels of increasing difficulty, each one for a period of 4 months: 1 month for the setup and tests phase, and 3 months of commercial service open to the public. During 2020, passenger operation has been limited due to the Covid-19 pandemic. In total a team of 18 trained safety operators secured the two shuttles on the three driving sites. The layout of the three areas differs as per the characteristics outlined below, see Fig. 1.

The setup phase on the first site started at the end of May 2019 in the Woluwe Public Park in Brussels. This first site consists of a park free of car traffic but with asphalted roads of 8 m width. The shuttles were used in operation during the summer season 2019 and the firsts objectives were to learn more about shuttle technology, train our staff in a relatively simple context, and invite the public to experience an innovative mobility service, in a friendly and relaxing context. There were 2 different routes with 5 fixed stops, for a total of approximately 1.7 km with a speed limited to 12 km/h. The shuttle service was free of charge and running from Friday to Sunday between June 2019 and September 2019 serving 5963 passengers and driving 1902 km in autonomous mode.

The second site, was in Solvay Campus in the north of Brussels. It is a private site with limited access, offering the advantage of allowing testing of shuttles on roads also used by cars and trucks. The site is more complex than the Woluwe Park in terms of routes that can be taken. The objectives of the test at Solvay were to refine the understanding of the technology of the two rented shuttles, train the staff in a context more like a real urban environment, launch and test an "on-demand" service and test the viability of the shuttles in a business environment. There were no fixed routes but 9 fixed stops. The shuttles selected the shortest way to go to the destination entered by the safety driver. The total distance being available for the 2 shuttles was approximately 1.7 km with a speed limited to 16 km/h. The shuttle service was free of charge, and running from Monday to Friday, from 9 am to 5 pm, between October 2019 and February 2020 serving 1143 passengers and driving 1200 km in autonomous mode.

The third chosen site was at the Brugmann Hospital in Brussels. It is a private site with public access, offering the advantage of roads shared with cars and trucks as well as bikes and pedestrians. The site is more complex than the two previous in terms of the routes that can be taken by the shuttles and of sharing the road space with many other users. The objectives of the test at Brugmann Hospital were to understand the flexibility of the shuttles in a complex city-like environment with unpredicted obstacles such as illegally parked cars, interaction with cyclists and heavy goods vehicles (HGVs), testing the shuttle service to ascertain if it would be suitable as a permanent use case and total cost involved, and test the viability of the shuttles in a hospital environment, with lots of people with reduced mobility capacities that may be in need of such a service. Here again, there were no fixed routes, but 10 fixed stops and the shuttles selected the shortest way to go to the destination entered by the safety driver. The total distance being set up and available for the 2 shuttles was approximately 1.2 km with a speed limited to 16 km/h. The shuttle service was supposed to be free of charge and running from March 2020 until June 2020. Unfortunately, the Covid situation made it impossible to operate inside the hospital. The test was cancelled when

Table 1
Demonstration site data information.

	Brussels			Linköping	Turin
	Woluwe	**Solvay**	**Brugmann**	**Campus Valla**	**Piedmont Capital**
Starting date	2019–06–20	2019–10–28	2020–03–13	2020–03–10	2020–02–01
Closing date	2019–09–20	2020–02–14	2020–03–20	Preliminary end 2023	2020–07–31
Numbers of AV	2			2	1
AV models	2 EasyMile EZ10 Gen2			1 EasyMile EZ10 Gen2 1 Navya DL4 Arma	1 Olli
Safety drivers	18			8	10
Lengths of the driving track	1700 m	1600 m	1200 m	2100 m	700 m
Max AV operational speed	12 km/h	16 km/h	16 km/h	16 km/h	33 km/h
Min AV operational speed	5 km/h	5 km/h	5 km/h	6 km/h	10 km/h
Number of AV bus stations	5	9	10	8	6
Shared connection to PT	1	1	1	3	0
On Demand	No	Yes	No	No	Yes
Free of charge	Yes	Yes	Yes	Yes	Yes
Numbers of passengers	5293	1143	0	2263	150
Driven milage	1902 km	1200 km	20 km	6776 km	500 km

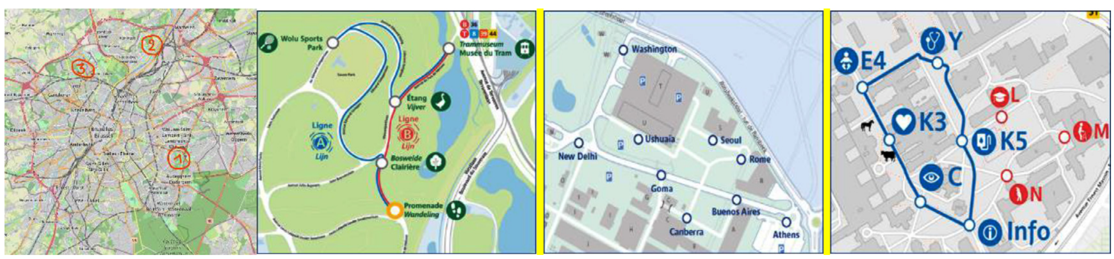

Fig. 1. Operating maps of the Woluwe Park (1), the Solvay site (on demand) (2) and the Brugmann Hospital (3).

the setup and test phase were just finished, the day before starting the public service.

3.2. Linköping

In 2019, work began to establish a demonstration area with two automated shuttles in Linköping. The city is located ca. 200 km south of Stockholm and is one of Sweden's fastest growing cities. The population of 157,000 at the beginning of 2021 is continuously increasing. Linköping is currently the fifth largest city in Sweden and is part of the expansive East Sweden Business Region. The demonstration site in Linköping is located within the Campus Valla area at Linköping University, with more than 27,000 students, next to Linköping Science Park. The demonstration site is a collaboration between Swedish National Road and Transport Research Institute (VTI), Linköping University, Transdev, Östgötatrafiken, Rise, Linköping Municipality, Linköping Science Park and Akademiska Hus. Two multi-brand shuttles operate within the Campus Valla area, and a third AV is in the planning stage. At the VTI depot, a total of eight safety operators manages the daily operation. The route has eight fixed bus stops, it is approximately 2.1 km, and takes around 15 min to complete. The speed limit on the route ranges between 6 and 16 km/h. The shuttle service, which is free of charge, has been running between March 2020 and June 2021 serving 2263 passengers, a limited number of passengers due to Covid-19. The aim of establishing the demonstration site in Linköping is to contribute to a better travel experience for a wide range of users and to assess the cooperation between involved stakeholders, including multiple OEMs. Another objective is to provide a robust, safe, and reliable operation for so-called first/last mile service. The operation in Linköping have also been extended to cover a recently developed residential area nearby, called Vallastaden. The extended route will provide a means of transport for the first and last mile to PT trunk lines close to a school and a residential home for elderly. It will be supported by an adaptive Mobility as a Service (MaaS) solution with the end users in mind. The extension, which is part of the EU funded SHOW project (https://show-project.eu/), aims to evaluate the effect AV shuttles has for the independence of the elderly and school children.

3.3. Turin

Bringing an automated shuttle to the Piedmont capital, the first deployment of its kind in Italy, is part of the whole strategy of Turin Municipality. The city is highly committed to initiating the penetration of autonomous mobility, facilitating the process and fostering cooperation between private enterprises, local facilities, academia and civil society. The vehicle involved in the Turin demonstration is the Local Motors Olli shuttle, a self-driving (autonomy Level 4), electric, 3D-printed shuttle, developed for urban mobility and designed with particular attention to accessibility and sustainability. During the demonstration, the shuttle provided transport services within the International Training Centre of the International Labour Organization (ITC-ILO) campus. ITC-ILO is an advanced technical and vocational training institution located in the heart of a riverside park in Turin. The Centre is dedicated to the pursuit of learning and training to reach the UN Sustainable Development Goal 8: "Promote inclusive and sustainable economic growth, employment, and decent work for all". Entrance to the campus is open only to employees, students and booked visitors. Still, the campus is an area characterised by traffic mixed with pedestrians, bicycles and motorised vehicles, (i.e., employees are allowed to enter in their own car).

The demonstration period took place between February and July 2020. The shuttle ran along a 700 metre route at an operational speed between 10 and 33 km/h. The users of the transport service, which was free of charge, could access the shuttle by standing at one of the six stops along the route, without having to book the service. In total, about 150 users boarded the shuttle during the test programme: about 80 campus employees, in addition to about 70 guests and other participants.

This demonstration is a forerunner for the actual experimentation that will be carried out in Turin in 2021–2022 within the H2020 SHOW European project (https://show-project.eu/), where two autonomous Demand Responsive Transport (DRT) shuttles will provide flexible public transport services to special categories of users in a real traffic environment.

4. Method

Preparing and implementing operation with autonomous shuttles in cities is something new and a rather disruptive business that, if it works, has the potential for market changing the area of mobility and hopefully replacing the highly car dependant transport system to a more shared mobility solution. This paper aims to identify the path toward future implementation and to provide a good understanding of common limitations. The work is explorative, identifying pros and cons with such an innovative operation. The paper describes, in a structured way, similar experiences from sites setting up demonstrations, formulated as lessons learned. This can be used to identify important areas for improvements to support future AV operations and to avoid repeating the same mistakes at other coming sites.

The method is based on a collection of experience from 5 sites in 3 countries, here seen as Cases. Each site has identified their lessons learned and the experiences that are common at all sites are described below.

5. Lessons learned

In general, a substantial amount of planning and preparation is required before realisation of an AV shuttle operation at a new site. Tasks include setting up stakeholder groups, applying for grants or budgeting for running the operations/demonstrations, selection of route or area to operate in, identifying use cases, benchmarking and negotiating the type of AV shuttles to use, applying for approval for operating, information and communication with users, etc. It is important to have a good understanding of the lead time and requirements for approval when establishing a new site, a process that differs depending on national regulations and legislations. Based on lessons learned, mitigation areas have been identified covering: other road users and road infrastructure, weather dependant operation, season dependant operation, improvement of localisation, digital infrastructure, design and working conditions, and citizens' user experience, each serving as headings in the text below. The sites operate different brands and number of shuttles, different types of infrastructure and varying local conditions. The focus here is, however, rather on generic lessons learned with the aim of facilitating start up of similar operations elsewhere and to avoid spending unnecessary time and resources on previously recognised issues.

5.1. Shuttle interactions with road users and infrastructure

5.1.1. Interactions in relation to those outside the shuttles

During AV shuttle operations, it is important to consider passengers as well as other traffic participants and road users outside the shuttle. It is essential to ensure that the AV shuttles interact safely and smoothly with vulnerable road users, as well as drivers of other vehicles. Furthermore, avoiding misunderstandings of interactions and intentions is vital. Based on the experience from the three sites involved in this paper it can be concluded that, up to now, standards for how to handle interactions safely and clearly do not exist. Different shuttle OEMs use different types of sound, activation of sound, lights, etc., that do not support a clear understanding of the shuttle's intentions and safe interaction with other road users. This situation becomes very demanding for visually impaired users, since it is not possible to ascertain if the sound is addressing you or someone else, whether it is a warning or information, etc.

The shuttles used in our sites are equipped with light detection and ranging (lidar) sensors for navigation, or rather localization, and obstacle detection. The technology of the lidar sensors and its computational power reduces the reaction time and braking distance compared to a human driven vehicle. This can have consequences for those travelling inside the shuttles, where hard braking can cause abrupt movements of the occupants and the safety operator. In addition, the lidar sensors are not always compatible with existing safety road constructions such as speed bumps, elevated crossings, etc., with the most common issue being when the lidar sensors identify such safety measures as objects and initiate a (hard) braking event.

Driven by requirements to obtain permits, where risks of interaction with other road users play an important role, the shuttles typically prioritize external safety over safety considerations for those inside the shuttle (internal safety). Research is ongoing about how to better balance deceleration with maintained safety from all these perspectives.

Improvements in sensor technology used to detect obstacles (cameras, lidars, radars) make it possible to better identify and classify objects in different categories. Based on this classification, shuttle providers tend to reduce the number of hard braking occurrences. A better understanding of the nature of the obstacles in the vicinity of the shuttle brings different opportunities for improvements. For obstacles that appear to be stationary, it would be possible to overtake some of those obstacles standing in the way of the shuttle. Some shuttles stop and analyse different alternatives before passing by any obstacles and returning to its route; others overtake without ever stopping. In some cases, the shuttle may request permission of an operator (locally or at distance) to allow the overtaking procedure. Detection and classification of moving objects in the vicinity of the shuttle, such as pedestrians and other road users, are also in the process of enhancement, which facilitates prediction of the future position of a detected object based on its current position and speed. It is then easier to proactively reduce the speed of the shuttle in specific cases and thus reduce the hard braking.

Recommendations: In the wake of the realization of these improvements we recommend injury mitigation actions in terms of seat belt usage for the protection of shuttle riders. In one site the shuttles have been equipped with a rear sign asking trailing vehicles to keep a safe distance to the shuttle.

5.1.2. Overtaking situations

The risk in circumstances when other vehicles are travelling in the same direction behind a shuttle is that the shuttle initiates a hard braking event in overtaking situations that occur too close to the shuttle. The problem arises when the lateral and/or frontal distances are too close to other vehicles during the overtaking event, see Fig. 5. If the shuttle deems the distance clearance too short to be safe, the shuttle will slow down or brake to increase its safety distance, see Fig. 3. In certain circumstances, this type of situation may lead to secondary problems for the vehicle behind the shuttle, increasing the risk that the driver in the car behind does not understand the reason for the shuttle reducing its speed. Hence, the driver of the vehicle behind might be encouraged to overtake the shuttle, which may cause additional interference with the shuttle's safety clearance distance, and thus initiate an abrupt braking event in the shuttle. Figs. 2, 4

Recommendations: Overtaking the shuttle may lead to safety risks. Ideally, vehicles travelling in the same direction as a shuttle should not be encouraged to overtake it, although overtaking may occur if the lane or road is wide. On the other hand, if overtaking is indeed taking place the road should be wide enough to allow other vehicles to keep a sufficient lateral distance to the shuttle.

5.1.3. Oncoming traffic and other road users

Vehicles travelling in the opposite direction of the shuttle may cause problems. This can occur when the oncoming vehicle travels at high speed and the lateral crossing distance is not long enough according to the shuttle, see Fig. 5. The size of the “safety bubble” of the shuttle depends on its speed. If the shuttle moves faster, the size of the bubble will increase and objects on the roadside and/or obstacles inside the bubble will cause the shuttle to slow down or even stop. Those obstacles can be of different types such as moving obstacles, for example, pedestrians, bicycles or vehicles, or fixed obstacles such as an illegally parked car

Fig. 2. Overview of the Brussel areas; the Woluwe Park (2 km) (1), the Solvay (5 km) (2) and the Brugmann Hospital (2 km) (3).

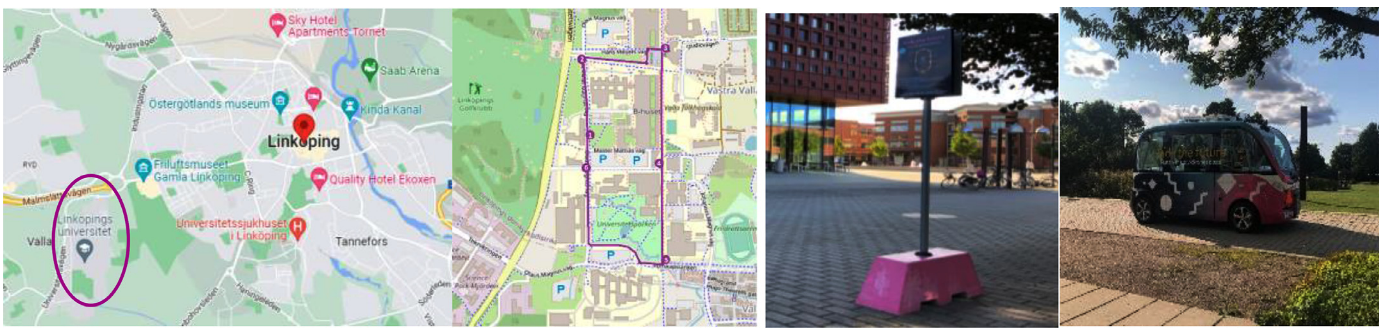

Fig. 3. Description of the Linköping demonstration site.

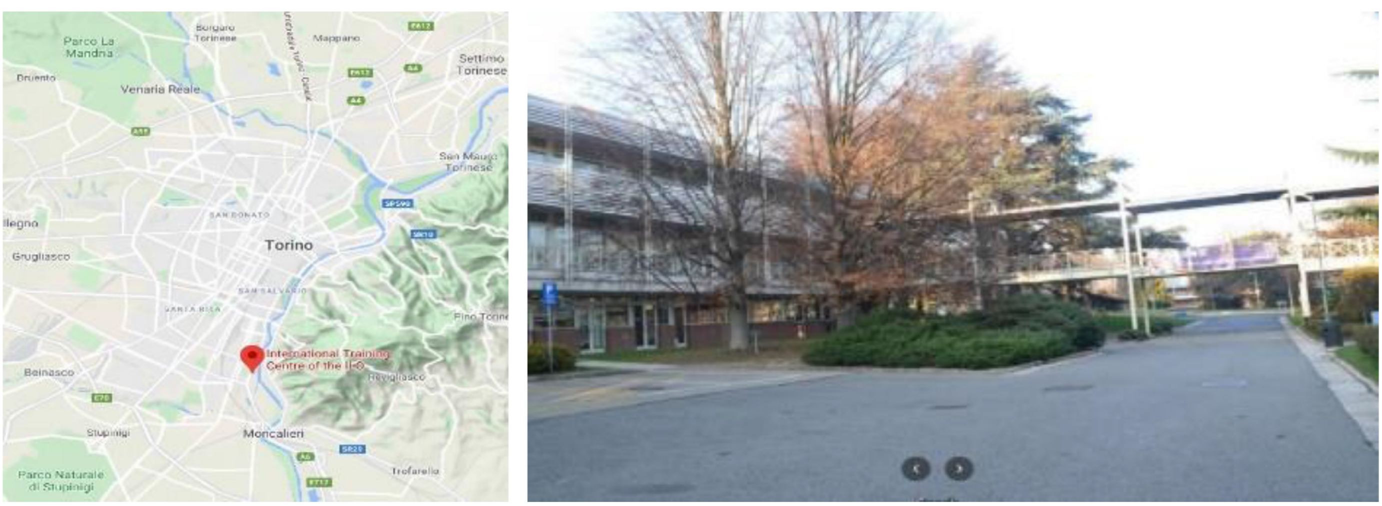

Fig. 4. Location of the Turin demonstration site.

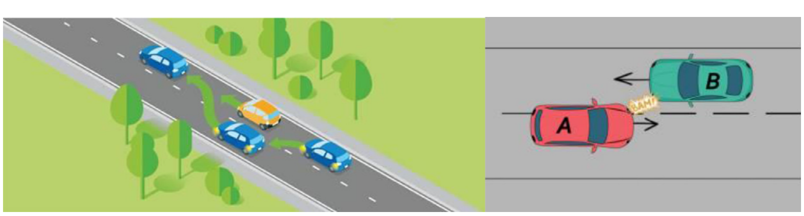

Fig. 5. Overtaking situation[1] and Oncoming situation.[2]

or a parked car with the tyres turned that would be detected as an unforeseen obstacle by the shuttle. Turning left is complicated in countries with right hand driving, as the shuttle cannot act intuitively if another vehicle is coming on its right. Hence, traffic lights, or safe stops, are required to secure any crossroad the shuttle would need to turn left or go straight forward at. Turning right is easier, but only if right priority is applicable at the crossroad. The opposite problems apply in left-driving countries.

Recommendations: Based on lessons learned, with regard to recommendations in relation to road infrastructure, it would generally be best to avoid adapting the road infrastructure for running the shuttle. Preferably, shuttles should be developed to handle existing road infrastructure. However, this is currently not the case, and it is thus recommended to adapt the road infrastructure, also taking speed into consideration, to avoid overtaking by other vehicles driving behind the shuttles as well as to allow a shorter distance between vehicles in the oppo-

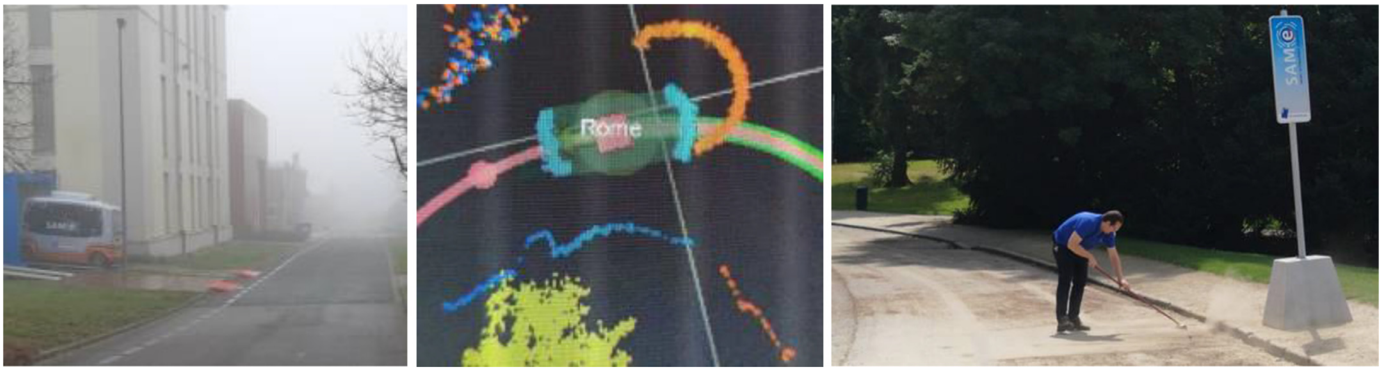

Fig. 6. Being stopped by fog detected as a wall by the LIDAR technology (left). The orange curve is the fog as detected by the front left lidar of the shuttle (middle). The blue curves are the fog as detected by the central front and rear lidars. Removal of dust from the road that triggers emergency stop events(right).

site direction. In addition, filtering functions to safeguard shuttles are not in opposition to the aim of the road design is required. Furthermore, feedback from safety operators, monitoring any unexcepted or hazardous situations, improvements on the spot, etc., must be taken into consideration.

5.2. Weather dependant operation

Obstacles identified by the lidar sensors, such as grass, tree branches or flowers moving in the wind, cause problems for the shuttles. The shuttles will recognise such obstructions as moving obstacles which makes the shuttles slow down, an issue that is overlooked during the mapping process.

The lidar technology fitted on some shuttles detect water, dust and leaves in the air, increasing the risk of detection of unforeseen obstacles appearing suddenly and instigating hard braking events. Below is an outline of some common issues encountered at the sites described in this paper:

Rain is not detected by the lidar until the drops reach a certain size, that will be identified as many small obstacles. The shuttle then starts to “lag” (random speed reduction) and finally stops. Fog is detected by lidar sensors as actual walls surrounding the shuttle and it will therefore come to a halt as it perceives fog as an object too close in its field of view, see Fig. 6.

Dust on dry and windy roads is problematic as dust might be perceived similar to fog and in certain circumstances even more critical than fog. As shuttles driven over a certain speed can whip dust up by themselves, the lidar technology fitted on the shuttles will suddenly see a wall of dust appearing and trigger an emergency stop (hard brake) event. If the shuttle is not “taught” to recognise this particular obstacle, each journey it will continue to stop on the same dusty area on the road, until the dust is removed.

Recommendations in relation to weather conditions, based on lessons learned:

Using radar (sound based, not light based) technology to complement the lidar might be a solution to mitigate weather dependant braking and stopping issues. The shuttle should then be able to recognise various weather conditions and decide to utilise the radar instead of the lidar in case of fog, for instance. Another solution might be to use Artificial Intelligence (AI) and developing smart filtering functions and algorithms that learn to discern what to act on and what to ignore. Solutions using AI training looks promising to avoid future emergency stopping events due to temporary obstacles.

5.3. Seasonal dependant operation

Autonomous shuttles use different systems for their precise positioning on the pre-programmed maps. Global Navigation Satellite Systems (GNSS) and lidars are two of these systems that are sensitive to their surroundings. Growing grass and trees have the potential to cause problems, hence mitigation strategies should be implemented in green areas on the verge of the roads. Should long grass moving in the wind appear in the safety bubble of the shuttle, the shuttle will slow down or even stop completely The distance between the lawn and a driving shuttle should be far enough or else the grass must be mowed on a regular basis to avoid being detected by the lidar. The same is true for all kinds of vegetation that can enter into the safety bubble of the shuttle or reduce the visibility of the lidar. Similarly, objects such as plastic bags, birds, etc., can also instigate an abrupt braking event. It has been difficult to find a suitable solution for birds and other animals, therefore it would be beneficial in future filtering to integrate functions based on gained experience. An abundance of trees covering the sky above the roads used by the shuttles would require trimming or else speed reduction must be accepted. Although it is easy to understand that GNSS signal coverage is reduced in tunnels and underground, it might not be obvious that roadside trees have a similar effect, reducing the capacity of location precision and consequently affecting the speed of a shuttle. Keeping the branches trimmed is not only a budget issue, it also affects the landscaping of cities dependant on trees as well as the risk of damaging the trees.

Snow is another barrier for smooth operation. Besides snowflakes being identified as obstacles, like dust and leaves, snowbanks are also detected by lidar technology as fixed objects, see Fig. 7. To avoid triggering hard braking events, this issue may require further maintenance to move the banks further off the lane.

Recommendations: Rather than continuously clearing the environment from moderate seasonal dependant issues it is recommended to further develop the shuttles. Furthermore, it would be preferrable to work towards a solution that can ‘teach’ shuttles not only to identify that an object is ahead, but also what the object is and whether it is necessary to act on it or carry on. To this end, AI might be a powerful tool to be incorporated into shuttles.

5.4. Improvement of localisation capacity

The shuttles must be certain of their precise position at any moment in real time. For that purpose, different technologies are simultaneously used to keep to a satisfactory level of precision:

- GNSS, depends on satellite coverage, and is improved using Real Time Kinematic (RTK)
- RTK positioning depends on the data connection availability (4 G or higher)
- Odometry to extrapolate the present position based on last known position
- Lidar sensors, that compare the position of fixed objects in sight with their recorded positions on the registered mapping of the site.

Fig. 7. Snowbanks causing stops.

Fig. 8. Signs to support the lidars for orientation.

Lidar sensors are used to geolocate the shuttles. To compare its location with the map as well as detect obstacles in real time, a lidar sensor must always be able to distinguish certain fixed points on the shuttle route. As it is stationary, a building is a suitable geographical reference point, while trees are less appropriate since they move in the wind and low vegetation grows with time. For example, a specific environment such as a desert or a forest can render the lidar location technical tool unusable, as there are no permanent reference points. To reinforce the location and to guarantee safe operation, some shuttle brands require detection of visual aids such as physical signs or flat panels by the lidar sensors for additional physical reference points. For the shuttles to detect the signs, the covering area is required to be large (1 × 1.5 m) and preferably made of a material that is not reflective or in an absorbent colour, see Fig. 8. As such signs are not always visibly attractive, some countries require a building permit for signs displaying information. Therefore, installation of physical signs should be avoided or only installed if necessary in future operations.

Recommendations: The most promising solution is to further develop the localisation functionality rather than adjusting the infrastructure to make it suitable for AV shuttles. Although common for obstacle detection, shuttle manufacturers are less likely to use lidars for localisation purposes. The issues caused by lidar based localisation systems should soon be eliminated by the progress in GNSS + RTK and odometry systems combined with the use of cameras. Our recommendation is to double check if physical signs are necessary before installation.

5.5. Digital infrastructure

If on the one hand mechanical components of an automated shuttle are quite simple, autonomous driving, on the other hand, requires continuous contact with remote systems and considerable processing power onboard the vehicle. All the elements of this type of ‘travelling ICT system’ and their smooth operation to govern a self-propelled vehicle is sometimes critical: the future of digitalisation is evolving and AV shuttles are a part of and depends on the development of these systems. The performance of the shuttle operation can be seen in real time on a heatmap running on a screen inside the shuttle. However, it is not possible to see the reason for malfunction of operation to identify why a shuttle has stopped, which would have been very useful for troubleshooting. In future, it would be of great importance to receive feedback from the system about what has happened and why a certain decision was made. The unwillingness of OEMs to share their application programming interface (API) is also producing some extra work, since most customers need to evaluate the shuttles’ performance and hence require data of a rather high resolution, to be able to measure and calculate basic Key Performance Indicators (KPIs) such as acceleration, deceleration, etc.

Recommendations: To support and encourage future development, open APIs is something to recommend, this is also in line with the trends of innovation development in general.

5.6. Safety operators’ working conditions

Hard braking is causing problems for safety operators, resulting in safety operators having been injured at two sites. The OEMs do not share information about the reason behind an external hard braking event, which is problematic for developing and applying mitigation strategies. Future development of maps displaying shuttle routes should also highlight any reasons for en route hard braking events and of course use learning algorithms to avoid similar stops in the future. In order to prepare safety operators for hard braking events, there is also the potential of informing the safety operators that a stop is imminent. It might also be useful to incorporate a solution to support safety operators so that they do not to fall during braking events, especially when the control unit is in the hands of the operator who therefore is unable to hold on to something in case of a braking event. For this purpose, one of the sites has equipped shuttles with an extendable safety arm that should make the working conditions more stable for the operators, see Fig. 9.

The safety operator on the shuttle is responsible for the operation as if they were driving a conventional city bus. Their tasks have very little to do with that of a traditional driver. Apart from a certain aptitude for manual driving using a joystick instead of a steering wheel, the vehicle is mechanically ‘simple’. The real skills, on the other hand, are of IT nature, linked to start-up procedures, continuous verification of the alignment of various processing and telecommunications systems, restart procedures in the event of unexpected events and data backup at the end of service. In terms of future work, this aspect is a concrete example of how autonomous technology can require greater professionalism of employee profiles without necessarily having a negative impact on employment. The driving task in a shuttle is more monotonous and the risk of driver fatigue is a fact. Another difference compared to driving a normal bus is inattention due to involvement with the passengers. A further lesson learned is that the behaviour of shuttle passengers is a bit different to travelling on a conventional bus, since the shuttle compartment is different, providing more space for other activities. The role of the operator is then also to make sure that all passengers, especially those with special needs, the elderly or children, are seated.

Some OEMs are now improving safety and comfort for onboard operators. Even if this issue would be eradicated once safety operators are not required in the future the experienced imbalance between internal and external safety also poses the question of how mature the shuttles are for passenger travelling without using seat belts. During operation, safety operators must pay attention not only to the external traffic situation but also internally to the graphic user interface (GUI). This is where vehicle specific interactions take place and where the driver confirms yields, checks vehicle status and communicates in general with the shuttle. Sometimes this can be demanding, especially if the operator is not a native English speaker, since the GUI is not configurable in any other language than English. There is a risk of failure in case the time available for action is limited. Also, the size of the control

Fig. 9. Safety arm to support safety operators during ride, developed by VTI, Sweden.

unit and the lack of somewhere to secure it when not in use, is not in line with good working conditions. Here the situation requires operators to keep track of the road, traffic safety and simultaneously care for passengers.

Recommendations*:* Working conditions for safety operators are taken very seriously and to date there is no clear timeline for when safety operators will be able to operate from a control tower, for example. Meanwhile, to guarantee a safe and fair working environment it is clear that the need for improving working conditions for safety operators is still a priority. This includes keeping the safety operator safe during braking events, a place to store the hand control, space to keep personal belongings (lunch, coat, etc.), a seat to rest on and measures to avoid slippery floors.

5.7. Passengers' experience, comfort, and safety

The interior design varies between shuttles. The design of the seats, especially when wooden seats are used, is not providing optimal friction conditions. One lesson learned is that the combination of no seat belt and wooden seats increases the risk of falling off the seat in hard braking events for users in clothes made of certain types of fabric. The recommendation is to provide seat belts on seats facing forward and if possible upholstered seats, until hard braking events can be avoided. It has also been noted that there are indications that citizens in urban environments, rarely travelling in cars, are not very familiar with seat belts. Hence it might be important to inform and educate passengers of the reason for wearing seat belts and how they should be worn.

Certain groups of citizens require different solutions to be able to use the shuttles safely and reliably, see Fig. 10. Blind persons, for instance, must be able to predict the shuttle's paths and actions, which is difficult at this point since the external and internal sounds and the activation of warning sounds are not generic. Different brands use different sounds, both with regard to the actual sound and when to use it (Pelikan, 2021). This is an area that needs further development. The role of the safety operator also looks different for groups with special needs. For example, the shuttles have not been fitted with exit buttons, and to date a generic way to inform where you are and where to get on or off has not been implemented. This needs further development to support safe and independent mobility, especially for on-demand solutions.

Due to Covid-19 it has been difficult to collect users' views on using the shuttles at the sites involved in this paper. A survey was undertaken at one of the sites, focusing on user acceptance of autonomous mobility (Caroleo et al., 2021). According to the survey results, the general experience of people who had travelled on the autonomous shuttle was positive (average score: 4.3 on 5) and they expressed a willingness to try such a service in real traffic conditions (87.5%). In general, the attitude towards autonomous driving is rather positive: people with no or few concerns prevail, however there is still a considerable share having at least some concerns. It seems that the travelers are open to the technology, as the majority (75%) believes that it will be a part of our daily lives in the future. The main concerns involve safety of vulnerable road

Fig. 10. Entering and exiting must be adapted to the users of special needs.

users and reliability of the technology. Due to these issues, the majority believes that a supervisor should always be available inside the vehicle, either in person or via immediate audio-video connection. Other frequently mentioned fears are the possibility of job losses due to automation and an increase in public transport cost. Amongst the possible applications, the most attractive situation when using the shuttles seems to be for mobility in congested city centers (41.7%). Several respondents (20.8%), also see the advantage of using autonomous shuttles in closed areas. The lessons learned is that an autonomous shuttle demonstration should consider the need to inform passengers about the context and the technology they are using,also to allow them to give their personal feedback.

In line with earlier research (Piatkowski, 2021), the experience to date indicates that novel users, or so-called early adopters, are very positive in comparison to other users who are not so positive. In the Brussels site, 70% of the users reported to enjoy travelling on the shuttles (Feys et al., 2020). In studies on users with special needs, it could be seen that there is a need for a more standardized way of handling communication during interactions with those outside the shuttle. This applies to pedestrians, cyclists as well as other car drivers.

Recommendation: The recommendation is to provide seat belts on seats facing forward and if possible upholstered seats, until hard braking events can be avoided. But also to engage user to use and to collect a more mature understanding of their experience, needs and whishes.

5.8. Charging and vehicle maintenance

This technology is in development, with continuous software updates. In several instances essential measures have been necessary by dedicated shuttle manufacturer staff at the site, which causes long lead times. The shuttles run on electricity and general standards are in place today for charging electric vehicles. One of the lessons learnt is the importance of checking that some of those standards are applicable for the shuttles at a particular site. If several shuttle brands are used at a site, then there is a risk that more than one solution is needed to cover both short and long-time charging, i.e., 1 phase or 3 phase electrical outlets configured with 10, 16 or 32 A. It is relevant to consider charging possibilities and their technical requirements already during the negotiation phase with the OEMs.

Closely related to the charging topic, to not damage the batteries, it was found that the bus depot must be heated during wintertime to avoid temperatures below 0 °C. This is an issue if you use cold depot solutions, especially for countries in with cold winter climate.

Cleaning and maintaining the AV shuttles is different from cleaning a conventional bus, especially the exterior as this requires specific competence and special procedures to ensure sustained performance of the sensors and the technical hardware. This is not always possible to guarantee, and staff training is necessary to avoid issues with lidar sensors, cameras, odometers, antennas, etc. On-site infrastructures are needed to protect, charge, and maintain the shuttles, see Fig. 11. Another option is to move the AVs to and from the existing facilities of a local mobility operator each operating day. However, the problem is that most shuttles are not designed to be driven manually outside of their operating site and certainly not long distances (2 km or more). Hence, special transport with a flatbed truck would then be needed. An alternative option, suggested by some OEMs, is the classical manual driving mode, which facilitates shuttle operator to drive the shuttle to and from local facilities before and after operations, or if in need of specific maintenance. Never-

Fig. 11. Flexible garage solution.

theless, a driver's seat and a steering wheel would be required, making the shuttle look more like a classical vehicle than an autonomous shuttle.

Recommendation: prepare for charging, cleaning, and maintaining taking into consideration the shuttle specific requirements and guidelines. Specific knowledge is needed.

6. Discussion

Already in 2017, Union internationale des transports publics (UITP) together with Transdev, stated that public transport offers the quickest development path to full autonomy because it can start operating in a limited area (UITP, 2017). Going back to the Vehicle Automated Driving Systems ((SAE), 2016) and Level 4 shuttle operation, it might be concluded that the policy brief from 2017 was very optimistic. The lessons learned from the demonstration sites in this paper clearly show that even though specific areas are used for operation, several issues remain.

As the shuttles are not yet able to operate freely on any road, a site assessment is the first required step for operation. From this assessment, usually realised by the shuttle provider, a lot will be learned about the operability of the chosen roads and the infrastructure adaptations that will be required to reach a suitable level of safety. Those conditions are generally also in line with the risk analysis that must be performed before receiving AV driving permission approval.

For wider use of shuttles it is however vital that shuttle development prioritises fitting into the existing traffic environment and eco system, rather than adapting the road infrastructure to enable the shuttles to run in the autonomous mode. Further development of the AV shuttles is vital to ensure that they operate smoothly in complex traffic situations considering lane and road width, shared spaces, snow, dust, rain, leaves, birds, etc.

The prospect of driving without an operator in public spaces has been postponed for the time being. The safety operator's task is to monitor what happens, interact if needed but mostly to support at shuttle stops, although formally they have the same obligations and responsibility as a driver of a regular city bus. Shuttles are programmed to run in special areas using virtual "tracks" and the driver is not provided with a steering wheel or a seat. Based on the lessons learned, it might be concluded that even if the safety operators were no longer needed, the need for dedicated resources responsible for the maintenance of the route, e.g. to cut the grass/trees, remove snow/sand, etc., or handle the shuttles remotely remains. Establishing a budget and a business plan is crucial, especially in relation to the practical problems that must be solved in order to have the shuttles up running. There is a risk that a support and maintenance solution for a shuttle with eight passenger seats will be far more expensive than having one driver on a regular bus with approximately 40 passengers.

A shuttle operation needs an ecosystem of stakeholders behind it, such as local and regional partners, landowners, safety operators, insurance companies and users. A shuttle is a new component and the demonstration sites included in this paper have required a lot of adaptations regarding road infrastructure before the realisation of the operation. It is recommended that the effort necessary to have AV shuttles up running should not be underestimated.

There is a wish to move from prototypes to vehicles that have passed a homologation process not only valid in a specific country but in all EU countries as soon as possible. The legal framework is still under development and is continuously revised and could even be subject to change during the tendering phase. As the shuttle OEMs focus on software automation solutions, they are often new players in the business of vehicles. Their level of maturity and standardisation (applying automotive industrial sector standards) is not yet mature enough for Public Transportation Operators (PTOs) that have experience of dealing with major industrial partners. Most shuttles available on the market or under development are still regarded as prototypes (Iclodean et al., 2020).

There are reasons to believe with regard to Safety Assurance of Self-driving Autonomous Vehicles that gaps of knowledge prevail (Tahir & Alexander, 2020). To the best of our knowledge, in mid-2021, there were no generic or standard approved AV vehicle types, and they are not adhering to normal standards as buses for PT do. This includes issues such as vehicle standards, but also issues related to turning light activation, braking light activation, etc. Simultaneously, a new trend has emerged of equipping existing models of classic vehicle manufacturers with autonomous technologies through industrial partnership. This could enhance the inherent technical quality of the vehicles and their integration with existing fleet management systems. However, the driving and driver perspective must still be addressed to achieve a solution ready for the market.

The importance of studying interaction and intentions with autonomous vehicles in real world traffic has been identified before (Pelikan, 2021). The authors underline that this is required throughout the entire rides, including aspects of driving that appear utterly mundane. To be part of a smooth traffic flow, autonomous vehicles must constantly coordinate with other road users and collaborate in joint manoeuvres with human driven vehicles

Hard braking events and stops represent one of the main challenges to solve. The balance between internal and external safety is important, as is a more “intelligent” handling of obstacles in the way of the shuttles. Even if hard braking events were experienced as an important topic for the future operation, it is worth mentioning that users at all three sites included here were very positive, just as in other studies (Bellone et al., 2021). Developing filtering functions and software algorithms to make sure that shuttles are not contradicting the aim of the road design, and to use AI to avoid hard braking event and stops when not required, is certainly promising (Martínez-Plumed et al., 2021). To safeguard pedestrians outside of the shuttle concurrently with making the shuttle operation smooth, new methods based on Short Range Communication might be of interest to develop further (Gelbal et al., 2020). Here also infrastructural investments with an integration of traffic lights at pedestrian crossings could be important to implement. At the same time all three sites recommend that to achieve an operation with high quality in a reasonable time there is no option to rebuild or adjust the infrastructure to support the shuttles. Future AV systems need to be able to operate in interaction with other vehicles, VRUs etc. using the existing infrastructure.

Another area of importance is the use of sound as a technology solution for information and warning, both to those onboard the shuttle and for those outside (Pelikan, 2021). The interaction with external road users is an important issue for achieving acceptance and trust amongst future passengers.

Despite the level of maturity of existing shuttles, the belief that there will be a demand for future last-mile automated services that can be integrated with MaaS concepts is strong (Bellone et al., 2021). However, the demand varies according to socio-economic and location-based conditions across different countries. The willingness to use shuttle services and pleasure in using them is seen as some of the main components for future shuttle success (Piatkowski, 2021). Similar results were seen in a study from Gothenburg, Sweden, in which the researchers highlight three different topics as the predominant reasons for not wanting to go on the shuttles: performance expectancy, route reasons and effort expectancy (Malmsten et al., 2020).

7. Recommendations

When starting a shuttle project for the first-time organisations most likely have limited knowledge about what to expect. Descriptions of shuttle projects and demonstrators typically share objectives and high-level details such as length and map of route, shuttle brand, expected or actual number of passengers etc. There are also processes for permissions and discussions about risks. There is however much less information about the difficulties you may run into when your shuttle travels on the road. This paper shares practical hands-on learnings from three sites – experiences that we ourselves would have found useful to know about when planning the sites described in this paper. The paper aims to contribute to avoiding known mistakes, to assessing use cases in a more efficient way, and thereby saving time and budget.

Based on the lessons learned, it is recommended not to underestimate the process and the time needed to bring an AV shuttle transport solution up and running, in contrast to purchasing a conventional bus. The PT operator/region or their partner, will be responsible for most of the preparation required for setting up the operation, even if the shuttle is purchased by another partner. As different shuttle brands have different strengths and weaknesses, it is important to have a clear view of what you aim to use the shuttle for before deciding what brand to select.

In addition, the results from this study show that further work is required to guarantee safe and smooth operation. The threshold between interior and exterior safety must be more balanced to safeguard both passengers onboard and that those outside are safe, a solution for this requires a good interaction/intention strategy provided by the shuttles.

Passengers, safety operators and those on the outside but in the vicinity of the shuttle, are exposed to the highest risks during hard braking events and sudden stops. While waiting for improvements to the actual shuttle vehicles, the following should be considered when setting up a demonstration site with AV shuttles:

- Consider road width, the risk of possible entrances into the shuttle’s “safety bubble”, and how to handle these situations.
- Implement an action plan for maintenance of the route surroundings, including trimming of greenery, handling of snow, etc.
- Ensure all passengers are seated, and those facing forward should be recommended to be buckled up.
- Secure the safety operator to avoid falls during braking events.
- Prepare the passengers and other road users before the introduction so the expectations are realistic.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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