Sohjoa Baltic

The Roadmap to Automated Electric Shuttles in Public Transport

Technology and Safety Requirements

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This publication has been made in the Sohjoa Baltic project (2017-2020) funded by Interreg Baltic Sea Region Programme. The aim of the project was to bring knowledge and competence on organizing environmentally friendly and smart automated public transport, provides guidelines on legal and organizational setup needed for running such a service in an efficient way.

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Foreword

The upcoming years are crucial to the development of automated driving in Europe. The technology has great potential to serve the public interest by improving the environmental sustainability of traffic and making transit safer and more enjoyable for everyone. At the same time, there is a risk that everyone will use his or her own private automated car, increasing the number of motorised vehicles on the road. Automated vehicles as part of public transport is a goal worth aiming for. Therefore, the Sohjoa Baltic project researched, promoted, and piloted the use of driverless, electric minibuses in public transport to secure the benefits of automated driving for society as a whole.

However, at the beginning we must answer the central question whether this innovation can be implemented within the existing legal framework. If this is not the case, the legal obstacles must be identified.

The technical and safety requirements document is intended to be used as a guideline underlining strengths and limitations of automation and electrification in mini-buses for last-mile urban transportation. Safety and technical requirements cannot be considered to be fully exhaustive as further research and studies need to be conducted, but rather as a starting point for future development of electrification and automation in urban areas.

This volume is intended to provide relevant legal information for persons or organisations interested in integrating automated driving into the public road system. It identifies the main implementation bottlenecks and gives practical insight into the requirements that must be fulfilled before an automated vehicle can be operated on public roads. Examples from practice illustrate the explanations.

About Sohjoa Baltic

The Sohjoa Baltic project developed the knowledge and competencies required to organise environmentally friendly and smart automated public transport by researching, promoting and piloting automated driverless electric minibuses as part of the public transport chain, especially for the first/last mile connectivity. It also provides guidelines on the legal and organisational frameworks needed to operate a service of this kind in an efficient way. The Sohjoa Baltic consortium has partners from Finland, Estonia, Sweden, Latvia, Germany, Poland, Norway and Denmark with expertise in transportation planning as well as legal expertise combined with a strong technical understanding.

Sohjoa Baltic brought autonomous small buses to drive demo routes in five Baltic Sea Region cities. The autonomous bus scans its surroundings and knows when to slow down or stop completely, if there are obstacles in the way. During the pilots there was always an operator on board.

With a run time from 10/2017 until 09/2020, the Sohjoa Baltic project was funded by the Interreg – Baltic Sea Region programme.

Executive Summary

This document is part of a series of volumes in the "Sohjoa Baltic - The Roadmap for Automated Shuttles in Public Transport", and it is targeted to professionals and administrations planning automated shuttles pilot projects and integration with the public transportation system.

The main topic covered in this volume concerns "Technology and safety requirements", the main content will describe the most recent state of the art in technology for automation and electrification in mini-buses for urban last-mile transportation, providing an overview of the challenges that arise when implementing automated buses as part of public transport.

The volume starts with the introduction to vehicle technology with specific reference to electrification and main electrical components required for battery charging, covering energy storage methods, energy density problems and charging infrastructure. This section exposes strengths and drawbacks of electrification, such as low pollution but also low energy density and infrastructure modification.

Then the automation problem is tackled from the perspective of vehicle control and environment perception. Here, the most recent technologies for vehicle localization, sensor equipment and artificial intelligence algorithms are described. Clearly, this volume does not pretend to be a full coverage of such an extensive topic but only to give a simple, and user friendly, overview of automation and electrification for last-mile transportation. Research in this field would be beneficial as localization accuracy must be increased, perception capabilities should also be increased including obstacle recognition and semantic segmentation.

The volume continues providing some experience about technical requirements that were asked to the tenders during the procurement process. Technical requirements are divided by vehicle requirements, operational requirements and routes requirements. From our experience it appears that our vehicle requirements and operational requirements had to be downsized to fit the current technological level. However, these pilot projects also push manufacturers to develop further in order to meet the demand from the contracting institutions.

Safety has been the most important issue during this project and so far the consortium did not experience any major risk for passengers or operators as safety components were pushed at the highest possible level. Our requirements and experience are summarized in the volume and it can be a starting point for others willing to continue with automated pilot projects. The main further development here would be how to release requirements (for example increasing maximum speed) while preserving safety for operators and passengers. The low speed was, indeed, one of the main issues to overcome for the integration in the public service.

I. Introduction

“What is the current situation of automated vehicles?”

“What does their future look like?”

“How can we use them safely?”

With the constant invasion of marketing messages about autonomous vehicles coming public expectancy about the technology is increasing sharply. Developers and technicians working in the field are though skeptical that such technology will be commonly available in the near future. The reason is twofold, hardware/software development not fully functional in any driving condition, and lack or a stable regulatory framework. In spite of these challenges, autonomous vehicles are seen as the future of transportation systems, and big strides have been taken in recent years thanks to the integration between vehicle mechanics and computer science. The latter has seen a turning point with the integration of machine learning and artificial intelligence that is currently driving most automated vehicles using data-driven controllers.

Nowadays, data is considered a valuable asset, generating massive investments though not yet enough to feed the data hunger. Indeed, the real question is: how much data should autonomous vehicles collect to generate a reasonable driving model? Currently, Google (with its subsidiary Waymo) has a fleet composed of roughly 55 vehicles tested for over 1 million kilometers per year, corresponding roughly to 30,000 hours of driving, which is more or less what one taxi driver does in his/her entire work life. Such data covers most of the common scenarios, different illumination conditions, and weather, but still not enough to be considered safe.

The reason why autonomous driving is not considered safe yet is to be found by analyzing the driving statistics, that, for most of the situations, involve previously seen and predictable scenarios. However, unpredictable events, though part of the real driving scenarios, hence probable, cannot be considered as outliers, as they can generate catastrophic events. This concept is known in economics as “the black swan”, but often neglected in AI systems, though fundamental to reach a high level of safety. The black swan is an example of an event that can occur with low proba-bility, thus part of the distribution, and with major effects on the system. Swans are white, should a black one still be considered as a swan? For an intelligent system to recognize unpredictable events effectively, it is necessary to acquire as much information as possible regarding the occurrence of such events that for autonomous driving correspond to safety loss. To answer the initial question, we do need more data describing unpredictable events and variability, but many hours of driving are required to find a black swan. The more research, the more knowledge, the more safety, the sooner autonomous driving will be a reality.

II. Technological background

Autonomy and electrification constitute enabling technologies for the next generation of the transportation system. In this section, these two concepts will be reviewed according to the recent state of the art

1. Electrification of Transportation

Industry and research are working together toward the electrification and automation of urban vehicles thanks to its potential to reduce pollution. Unfortunately, full electrification is not to be considered fully economically convenient yet, due to the high costs of batteries and the low energy density of electrochemical storage compared to fossil fuel, but fortunately, automation and intelligent technologies are contributing to approach this ambitious target by increasing the global efficiency of vehicles. Indeed, energy efficiency is currently one of the most important topics in the road vehicles industry.

The full-electrification of the public transportation system requires both vehicles and infrastructure to adapt to the new concept. The infrastructure should be updated with new charging stations around the urban areas, whereas vehicles should be equipped with high-density batteries. An important aspect of the recharging infrastructure concerns the choice between a unique station (centralized architecture), or the installation of many small charging points in each parking lot (distributed architecture). In most of the studies, the predominant direction is toward a decentralized architecture [1,2]. In [1], the authors compare centralized and decentralized architectures in simulation, concluding that a decentralized method would be more effective, also in terms of costs. However, they neglect a few important parameters such as the possible overloading in the electric grid due to too many vehicles recharging at the same time in the same area. Such a connection can be either wired or carried out in a wireless manner using magnetic inductors. The solution features the magnetic inductors at the bottom of the minibus and on the ground surface of the parking lot. As indicated in Figure 1, both systems could coexist in the minibus, where an automatic switch can select the power source based on the specific situation and location.

The basic components for the electrification are: Electrical motors, battery packs, AC/DC and DC/AC converters for recharge and power, cooling systems, cables and safety components [3]. Figure 1 provides a schematic example. From a vehicle point of view, electrification would bring countless advantages in terms of pollution reduction, heat generation, noise in urban areas and safety. However, the main lack in the use of batteries versus fossil fuels for transportation purposes is the lower energy density in electrochemical storage, defined as the amount of energy per mass. More specifically, the energy density in diesel is roughly 13,440 Wh/kg, whereas a lithium-ion battery has an energy density around 220 Wh/kg [3].

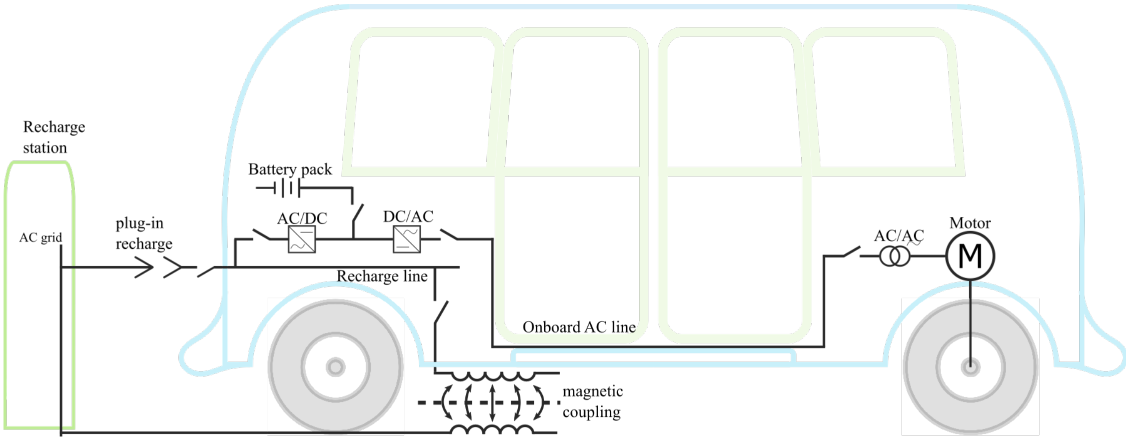


Figure 1: Electric components for a typical electric minibus

This means that over 60-times the weight in batteries should be needed to obtain the same amount of energy of fossil fuel. Fortunately, electric motors have a higher efficiency (over 90%), in contrast to combustion engines which have an efficiency less than 30% in optimal conditions and which goes below 20% in normal usage. From a reasonable estimation the additional weight can be between 10 and 20 times. This calculation does not pretend to be a precise estimation of the weight on board which may depend on vehicle specifications, but it gives the idea that batteries constitute an additional weight. As the efficiency of the electric motor is quite high, the efforts are currently concentrated on increasing the energy density and the efficiency of the recharging process. Following this line of research, the scientific world is investigating materials with high electrochemical energy density, going from old lead acid batteries [4] to Li-ion batteries [5], and even lithium-air batteries [6], which are expected to operate in the next decades with energy density comparable to fossil fuels.

One of the challenges in the field of Li-ion batteries is a phenomenon so-called “dendrite formation” [5], i.e., small spikes in the lithium anode, which cause short circuits between anode and cathode [7]. Although far from the market, a possible solution is to protect the anode using a graphene layer reducing the problem of dendrites and promising high energy density around 1000 Wh/kg [8]. Furthermore, a recent research on the same technology promises to triplicate the energy density of graphene-based batteries using an additional silicon layer [9]. According to the U.S. Geological survey there is enough lithium, in the United States only, to equip over 30 billion vehicles worldwide with lithium-ion batteries [10]. The current costs of lithium carbonate, required for batteries, is around 10 $/kg with increasing trend due to the increasing market demand. The other materials composing a lithium-ion battery such as cobalt oxide, manganese oxide, copper, and aluminium, are also inexpensive and common in nature.

2. Autonomy in Urban Transportation

In order to achieve the ambitious goal of safe fully autonomous driving within urban areas, vehicles have been equipped with a large number of sensors, essentially converting a normal car into a type of robot, adding new functionalities for control such as perception and Artificial Intelligence (AI) [11]. These basic concepts referring to the state of the art technology of autonomous driving are still controversial and discussed in the recent literature. For instance, which specific models of sensors and perception systems to use, or whether to use a precise model-based or an artificial intelligence approach to solve the problem of autonomous driving from end-to-end [12]. The latter approach copes with the problem as a whole using artificial intelligence.

The problem of automatic control of any system has been historically addressed using the classical control theory [13], that copes with the problem using the procedure of analysis of the physical process and synthesis of a controller [14]. Only if the physical process to be controlled is completely known, the synthesis of the controller can be solved. In case of autonomous vehicles the physical behaviour can change significantly according to the geometry of the vehicle, the load and the surface friction (for instance in case of rain or snow). A precise model that takes into account the number of variables analytically to synthesize a controller is often considered too complicated to be treated with classical theory. The process models of a wide number of vehicles are currently well approximated and implemented in market available Advanced Driver Assistance Systems (ADAS), such as cruise control, automatic braking, and lane keeping assistance [15]. However, a system built using the classical control theory lacks of reasoning, which is a required feature to build a fully-autonomous vehicle. On the other side, the artificial intelligence approach considers the vehicle to be a black box, and it automatically builds million connections between input and output removing the processes of analysis and synthesis of the controller.

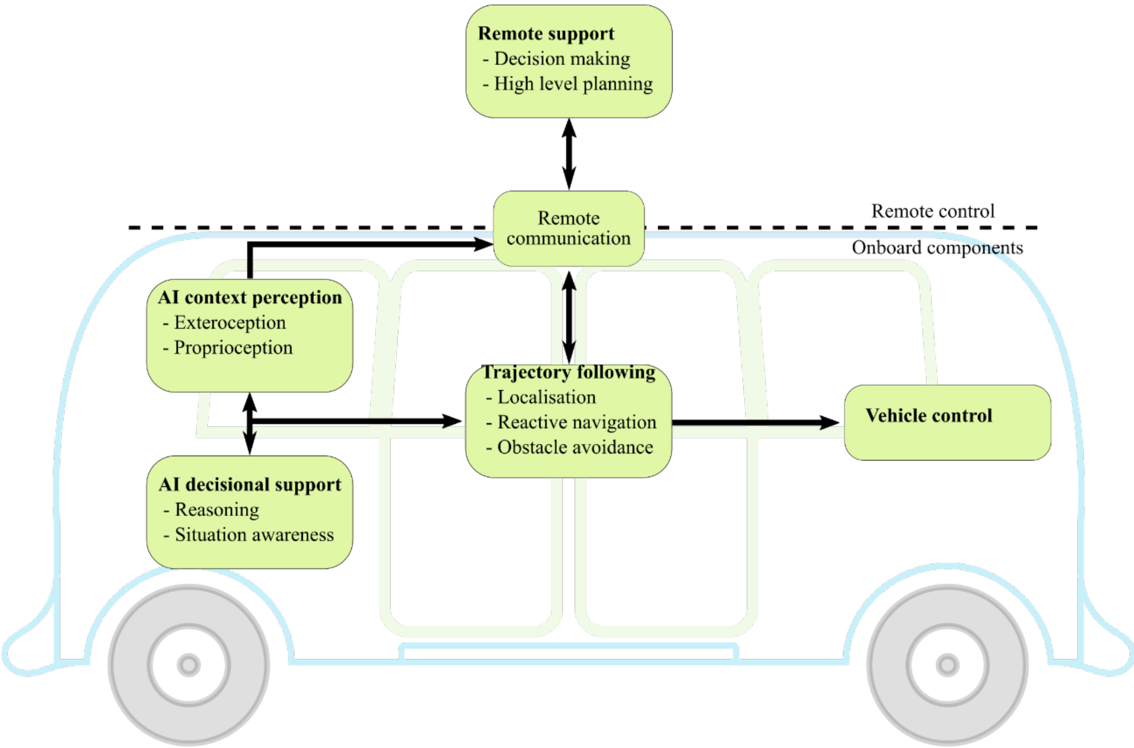


Figure 2: Main elements for situation awareness for an autonomous minibus

The approach is demonstrating efficacy in many practical scenarios, showing a high adaptation and abstraction ability. The work needed to synthesize such a control system is mainly based on large amounts of data acquisition and labelling to build known connections between input and output of the system [16]. Using machine learning, tasks such as scene recognition and situation awareness become solvable, giving to the vehicle the required level of reasoning. Although end-to-end approaches exist, they are somehow considered too abstract, removing the entire knowledge of the systems from the design, by replacing it with a black box, resulting in difficulties in detection and solving possible failures. As a result, the most reasonable approach does not exclude one or the other, but rather includes classical low-level control and artificial intelligence high-level reasoning used to support decision making. The real debate resides in the question: at which level should artificial intelligence be implemented? The most conservative streamline of research foresees the AI features to be placed at the highest possible level, limiting their task to scene recognition, such as pedestrian/cyclist/vehicle detection and in general obstacle recognition. Other approaches add artificial intelligence also for reactive navigation and obstacle avoidance, starting to include AI features into the high-level safety. Low-level control and safety are still implemented using the classical control theory.

The schematic in Figure 2 describes the main components required for safe autonomous driving of buses. Onboard components include AI for perception and decisional support, sensor data must be properly interpreted in the specific context providing reasoning abilities. Such interpretation is used for trajectory following, performing tasks such as obstacle avoidance and reactive navigation. The trajectory following also requires the localization ability to estimate the current position of the vehicle on the road. The most basic level is the vehicle control featuring low-level control architectures for acceleration and steering commands. Even though a remote station with the tasks of high-level planning and decision making should be included, most of the automation should be embedded on board. Indeed, while for tasks involving a small number of vehicles the autonomy using a centralized station with remote control is realizable, with a high number of driverless buses in an urban environment the complexity increases at a level that a centralized approach becomes infeasible due to the number of vehicles on the road. However, the communication between remote support and autonomous vehicles is important for the stability and efficacy of the entire transportation system. The remote support of decision making may include cloud computing for artificial intelligence support, this to access a large amount of data for interpretation and classification.

3. Sensors and perception

Vehicles are nowadays equipped with many different sensors that monitor the internal status like engine rotational velocity, temperature, global velocity etc (see Figure 3). The main feature that distinguishes an autonomous car or bus is that its own absolute position and the surrounding environment have to be measured. There is a distinction between proprioceptive sensors and exteroceptive sensors, referring to the measurement of the internal vehicle status and the surrounding environment. In this section, the main sensors and technologies used to integrate perception in autonomous vehicles will be reviewed.

Localization

The great strides of steering and velocity control systems allow vehicles to have a precise desired behaviour, but the driving policy must be defined according to up-to-date dynamic information (i.e., current pose and speed), which should be known or measurable with reasonable accuracy in order to navigate safely. In the field of ground vehicles, navigation is referred to as “every process or activity of accurately ascertaining one’s position and planning and following a route” (source: Oxford dictionary definition). Although this definition derives from the ancient meaning of travel on water, it completely fulfils the current connotation used in autonomous cars, underling the three main aspects bound to vehicles’ movement, i.e., self localization, path planning and trajectory following. The integration between localization, planning and following constitutes a navigation system. According to its capabilities, one can distinguish between fully-autonomous or semi-autonomous navigations systems.

In the view of the plurality of related applications, navigation methods may change according to the vehicle's workspace and sensors. Hence, indoor navigation is generally assigned to odometer sensors and visual techniques, whereas Global Navigation Satellite System (GNSS) generally accomplish the task of localization in outdoor environments. GNSSs estimate the position of a device on the Earth by trilateration of the signal from satellites in different orbits [17, 18]. Satellite-based navigation theory constitutes a wide and deep field of study and involves a large number of standards and notations. One of the most used is the World Geodetic System 1984 (WGS84), that constitutes an Earth-centred fixed terrestrial reference system [19]. In spite of GNSS-based localization systems fitting really well a large spectrum of applications in mobile vehicles, their accuracy may range within a few meters, whereas most applications in the automated driving require centimetre accuracy. Such precision is achieved using a base station. The GNSS is capable of measuring its distance from the satellites and the base station as well, improving the vehicle's positioning precision. This technique is also known as Real Time Kinematic, or RTK, and widely used in the field of vehicle-to-vehicle relative positioning [20].

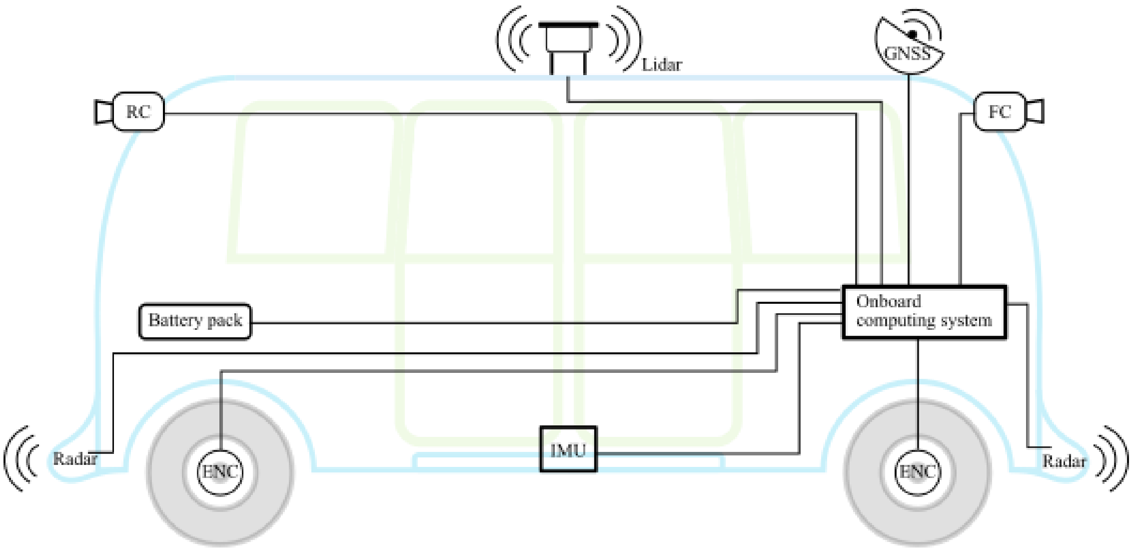


Figure 3: Typical sensors components for an electrical autonomous minibus. Sensor list: IMU, GNSS, laser, RC = Rear Camera, FC = Front Camera, ENC = Encoder.

Moreover, GNSSs need the direct connection between a receiver on the Earth and more satellites at the same time resulting in loss of accuracy in the case of hidden satellites, e.g., the so-called urban canyons, i.e., city roads surrounded by tall buildings [21]. To increase the global localization accuracy, research studies are moving toward the integration of GNSS technology with visual odometer systems. As a further issue, GNSSs perform really well in determining the global coordinates of a vehicle, but they cannot determine the exact pose of a vehicle including its orientation. At this aim, GNSSs are now integrated with Inertial Measurements Units (IMUs), or Inertial Navigation Systems (INS) [22, 23]. An IMU is a device able to measure vehicles' angular velocities, their orientation and gravitational forces by means of a combination between an accelerometer, a gyroscope and a magnetometer. One of the most used indirect sensor approach is the so-called dead-reckoning, which implies the integration of sensor measurements, typically the wheel encodes and IMU, to derive the current pose of the vehicle integrating wheel velocity information. The biggest limitation of dead-reckoning techniques resides in the unbounded accumulated error. In contrast, a direct sensor approach would offer the most accurate measure of the state of a vehicle, unfortunately some of the variables are not directly observable. Even though a GNSS can directly measure the vehicle position, the update frequency is typically low, varying in the range 1–20 Hz.

The important task of localization can also be approached from another perspective. Humans are able to localize themselves using space recognition capabilities, i.e., we use our own eyes to recognize salient attributes in space, and we locate ourselves in it. This implies the use of visual capability to improve global positioning. Most of the market players are exploring this way by using visual cameras and lasers to reconstruct the surrounding space and locate the vehicle in it. This technique is also known as SLAM or simultaneous localization and mapping [24, 25], and it consists in the estimation of both the map and the robot location at the same time based on visual data. In other words, the vehicle needs to build a map of the environment while navigating through it. The most recent research on SLAM brought this method toward the mapping of wide geographic areas, indeed probabilistic methods improve the global performance of the alignment such as the use of an extended Kalman filtering for the motion estimation [26]. One of the biggest problems with SLAM is the un-bounded error that increases over time. A widely used way to increase the accuracy of the mapping is the so-called Loop Closure [27]. This technique attempts to correct the alignment error every time that the estimated position of the robot is close to a previous driven position, as well as a loop [28]. Some market players (for instance Navya buses) decide to rely more on satellite-based localization, whereas others use more SLAM for the localization (EasyMile buses for example).

Scene interpretation

The analysis of the surrounding environment is performed in autonomous vehicles using visual cameras and 3D sensors for space reconstruction. The important task of these sensors is to reproduce the human eyes with robotic vision [29], giving the vehicles the ability to detect objects on the road. Normal visual (monocular) cameras can acquire 2D images, which makes it hard to have accurate direct distance measurements without adding a post-processing and, as a result, additional computational burden. Indeed, camera images constitute a projection of the 3D reality onto a 2D plane, and, for this reason, the distance information is lost during the acquisition. A way to retrieve this information is to measure the difference between two images from different angles, but at least two cameras would be needed. Considering that an autonomous vehicle would be moving, it is possible to estimate the distance of objects by measuring the variations between two consecutive frames acquired from the same (moving) camera [30, 31]. Even though the introduction of stereo cameras helps to measure distances using visual information, 3D sensors and laser scanners have higher accuracy, providing distance measurements within centimetre-accuracy in the far-range [32]. Such precise spatial information is fundamental for the control system to calculate the steering command to be applied to the vehicle in real-case scenarios to perform obstacle avoidance [33].

The most used sensors for ADAS features in cars are radars and ultrasonic sensors, implemented in the vehicles' bumper to detect the distance between vehicle and objects in tasks such as adaptive cruise control [34] and automatic parking [35, 36]. In the adaptive cruise control, the distance to the front vehicle is measured using the front radar and used as information to brake in case the distance is shorter than a designed threshold, hence maintaining the safety distance. The ultrasonic sensors are commonly used to implement automatic parking, a set of sensors is placed on the vehicle bumper providing a set of distances in the 2D plane, the planning system is then able to compute a trajectory to park the car in specific spots while maintaining the safety distance. Such sensors are commonly referred to as "time-of-flight" sensors [37], the principle is to emit a wave and measure the time between the emission and the moment when the wave hits back the receiver. As the speed of the wave is known, the distance can be calculated easily. The ultrasonic emitters uses ultra-sound waves, whereas the radar uses radio waves. The drawback of using ultrasonic technology is that the wave also has a wide beam, which implies that the hit surface can reflect the wave in different directions, the smaller the beam the better for the reflection [38]. However, using light waves such as in a laser or LiDARs (Light Detection And Ranging) the beam becomes smaller. LiDARs work with the same principles of radar and ultrasonic sensors but with the advantage of having a narrow beam providing incredibly high accuracy to distance measurements (within centimetre accuracy over a 200-m range). The main drawback of laser-based measurements for scene interpretation is the number of measurements required for the space reconstruction with the result of increasing computational burden.

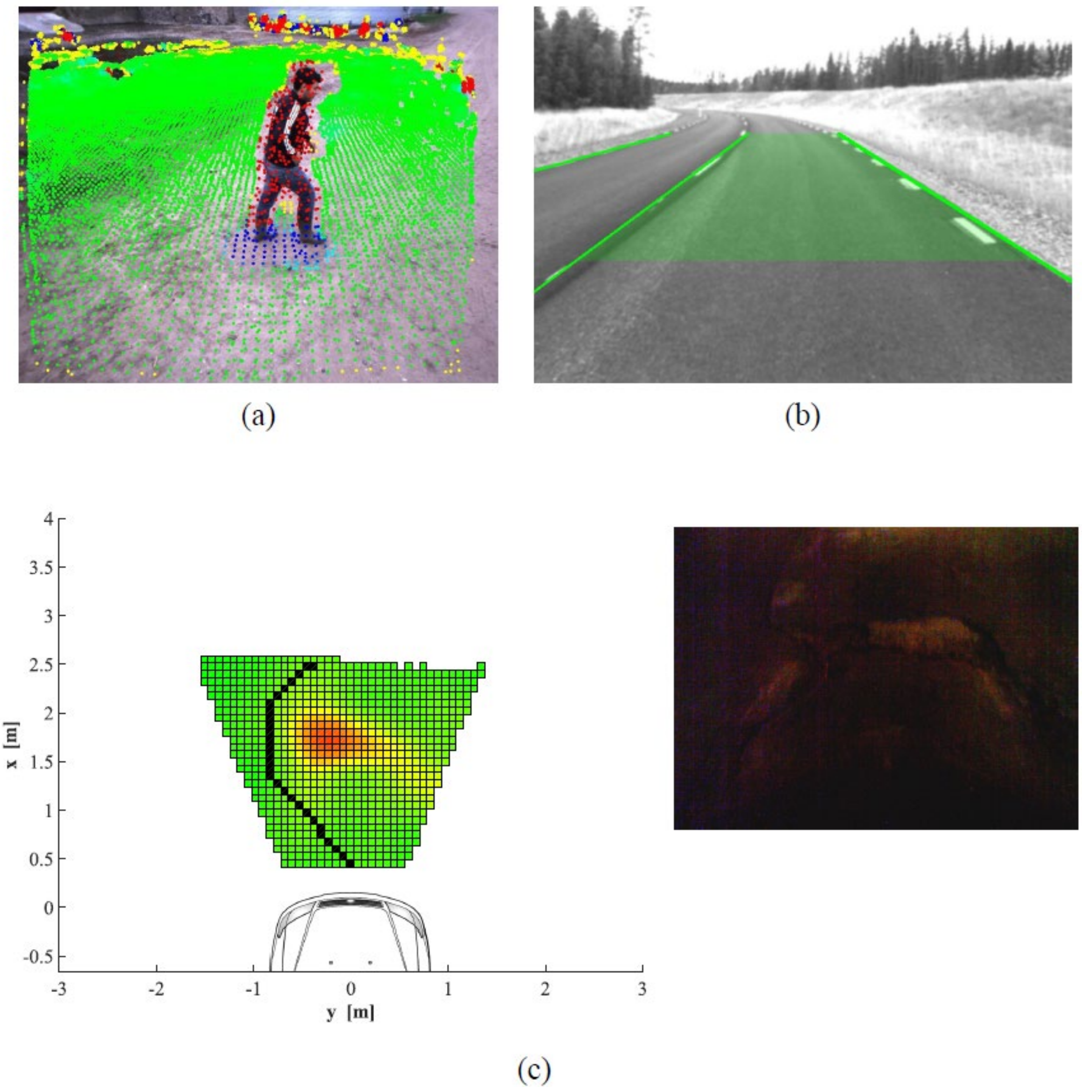
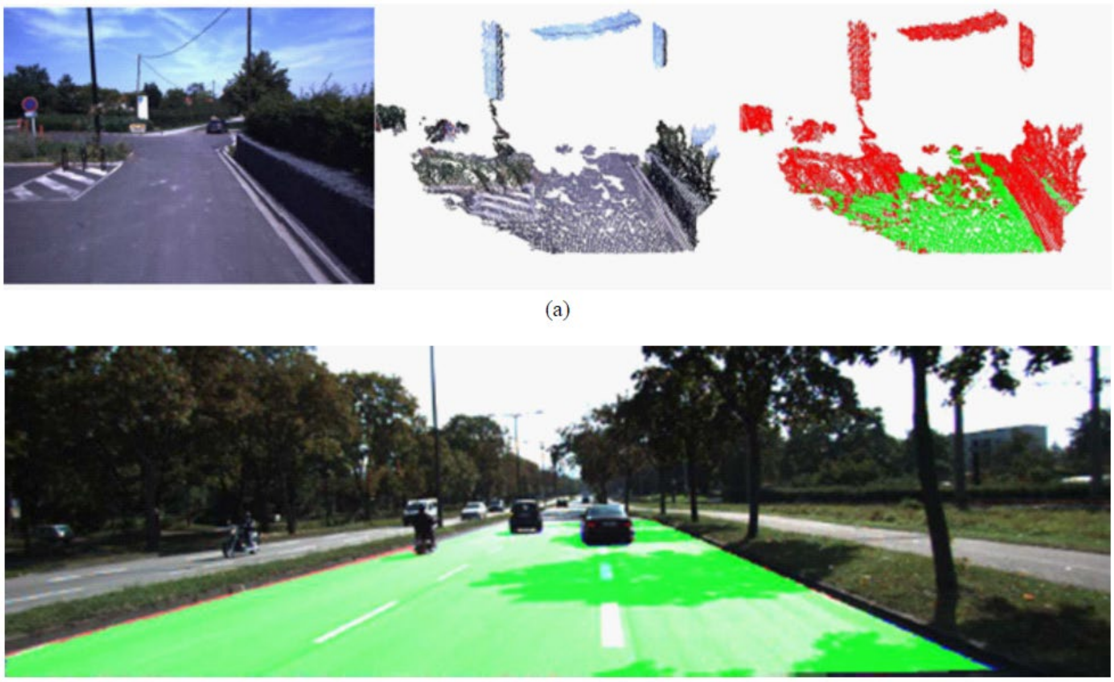


Figure 4: Examples of scene interpretation in which (a) a pedestrian is detected, (Bellone et al., 2013); in (b), the result of a lane detection algorithm is shown (Benderius et al,. 2018); whereas in (c), an example camera vision mixed with depth inform.

Visual cameras are also fundamental for tasks such as lane/pedestrian/vehicle detection [39, 30], a few examples related to the recent state of the art are shown in Figure 4. All those tasks are strongly required to be robust in future autonomous vehicles and nowadays technology already reached high accuracy in real road conditions. Benchmarks are available to measure the performances of artificial intelligence algorithms in these tasks. One of them has been realized by the Karlsruhe Institute of Technology (Germany), and the best results are continuously improved [41].

Lane detection is already in the market, implemented in ADAS systems for keeping the vehicle in the centre of the carriageway on the highway. The clear drawback is that this system does not work properly in case of not-clearly visible lane markings. Moreover, the camera being a passive sensor, it is strongly affected by lighting conditions such as high brightness or low illumination. Furthermore, they are also affected by weather conditions such as rain and snow or partially obscure lenses, while fog prevents the light reaching the sensor resulting in low contrast and blurred images [42]. Lasers are also affected by the same weather conditions, while radars and ultrasonic sensors typically work quite well in these conditions. The difference resides in the capacity of the specific wavelength to traverse small objects.



(a)

(b)

Figure 5: Road classification from 3D images using two different machine learning algorithms: (a) SVM classifier on 3D data, source: M. Bellone et al., 2017; and (b) deep learning approach on visual camera images enhanced with LiDAR information, source: Caltagirone et al., 2018.

An additional, but not trivial task, is the road classification and detection; the driverless vehicles require a deep understanding of where they are supposed to drive on the road and where they cannot. Hence, asphalt surface and side-walk have to be properly recognized. Figure 5 reports some examples of road detection using different artificial intelligence methods and different data sources, in Figure 5a 3D data from a stereo camera are used [43], whereas in Figure 5b, a fusion between camera images and LiDAR data was presented. In the recent state of the art, the road detection is well performed in clear and sunny conditions, the performance drops in case of night-time and not well structured road surface. All these conditions have to be better addressed in research with the final aim of improving safety in driverless vehicles.

As discussed previously, sensors working in all conditions simply do not exist, and for this reason robotic systems, such as driverless buses, rely on the integration of sensory information coming from different sources. However, there are many situations in which the information, or only part of it, can be missing. Hence, addressing the issue of safety in autonomous driving, the minimum level of operational requirements should be defined, but these parameters are not yet determined in any technical regulation or standardization. The definition of too strict parameters can result in a high number of not-operating conditions; on the other hand, too-low thresholds can lead to unsafe vehicles.

Finally, one last comment from a technological perspective is that automation may help to meet the demand of sustainability for future transportation, among many studies on the topic the consortium has conducted a simulation study on how speed profile optimization may help to save energy [44]. The study has conducted a simulation to optimize the driving speed of the autonomous vehicle in a realistic case involving the vehicle stopping in several places and loading a randomized number of people in the bus (this was to change the speed profile according to the load). Two different case studies have been considered, each involving a total of 10 different 2 km bus routes and two different average speeds. In the proposed method, the minibus follows an optimized speed profile, generated using a genetic algorithm. In the first case study the vehicle was able to reduce its energy consumption by around 7 to 12% relative to a baseline case in which it maintains a constant speed between stops, with short acceleration and deceleration phases. In the second case study, involving mass variation (passengers entering and alighting) it was demonstrated that the number of round trips that can be completed on a single battery charge is increased by around 10%.

Infrastructure versus vehicle-based automation

To build an effective urban transportation system, vehicles require a high-level of autonomy and intelligence. Two approaches have been studied in the literature during the last decades: infrastructure-based and vehicle-based. The first approach involves the realization of autonomous vehicles, completely reliable with the current technological level, and to modify the entire infrastructure in order to run autonomous vehicles in closed areas. This approach has been successfully used in many small-size case studies, demonstrations and few practical cases, one of them running at London's Heathrow airport. At the airport, the entire transportation infrastructure is a completely closed area, so no other users can interfere with the vehicles. The automation is then shared between vehicles and infrastructure, both will contain sensors to improve positioning and other parameters. This approach is effective and fully working as it strongly reduces the number of possible scenarios and for this reason unexpected conditions are nearly impossible, but the costs of the implementation becomes prohibitive in populated areas and long-highways.

On the other hand, in the vehicle-based approach the infrastructure should be untouched, and the entire automation must be embedded in the vehicle. This approach has had some experimental success, though not in any road scenario. The consideration of all the possible road scenarios constitutes the main limitation to build an effective driverless vehicle that should be able to handle unexpected conditions.

An important source of variability is the weather. Currently autonomous vehicles strongly rely on sensors, of which performance degrades quickly in case of rain, fog, snow and even change in illumination.

III. Requirements

1. Technical requirements

Building the procurement for the pilots, the consortium has defined many technical and operational requirements for the vehicles provided to be fulfilled. The requirements are divided in vehicle requirements and operational requirements. Many of the items were based on previous shuttle procurements, and what was learned from them. While some basic requirements that already feature any type of vehicle are considered as granted (such as seat belts, defogging, access to 12V power supply, USB ports, air conditioning, heat pump, etc.), others were specifically designed for the procurement of public electric autonomous mini-buses. This type of bus typically has at least 6 seats (with seatbelts) and is able to carry a maximum of 11 people, with some standing places. Though based on experiences of the pilots, standing in the buses cannot be recommended at this point due to possible sudden braking.

2. Vehicle requirements

Here we need to explain for each requirement what is about and why is needed.

Automation level 4 (SAEJ3016): Automation level 4 means that the vehicle must be able to drive under certain conditions without the help of the operator, which is required on board for safety reasons and for special driving conditions. This also includes the ability to automatically and safely overtake obstacles, automatically handle T-junctions, roundabouts/traffic circles and junctions led by traffic lights.

Usable on open roads with mixed traffic in automated mode: The automated bus must be usable on open roads with mixed traffic according to each state legislation. Some automated vehicles, with low automation level, are only usable in restricted areas, the bus usable for automated pilots must be able to handle mixed traffic in automated mode.

Access for disabled: Particular attention was given to the accessibility of the buses for everyone, for this reason an automatic ramp was required in the procurements. The ramp could be activated by the human operator opening up from the entrance to the sidewalk.

Lithium-Ion batteries: Lithium-Ion batteries are currently seen as the standard technology to reach a reasonable trade off between energy density and cost.

Electric driving range, at least 60 km: The vehicle must be able to drive without charging for at least 60 km in operating temperatures between -10 to +35 ˚C. Vehicle inside temperature for passengers 20 celcius (+/-3 celcius).

Onboard charger with standard connectors (SAE J1772): Public electric grid provides AC electricity, the vehicle must be equipped with inverters, safety electrical component with double insulation and standard connector to the electric grid. Operating temperatures (-10 to +35 ˚C).

Wireless charging: Magnetic coupling for wireless charging (or more precisely inductive charging) is not a strict requirement, but according to Sohjoa Baltic experience, it can be helpful to be able to stop in specific spots and recharge the vehicle as there is no operator on board to handle the cable connection. SAE J2954 (wireless power transfer) standard is the preferred type of device for this purpose.

CHAdeMO: is a fast charging standard that uses cable connection. Available standards are IEC 62196-3 IEC 62196-3 configuration AA, DC. Other types of connectors for fast charging may also be used such as Combo2 (IEC 62196-3 configuration FF, DC), and Type 2 (IEC 62196–2, AC).

Operating temperature: The mandatory operating temperature was requested to be -5°, +35°C according to the climate data in the regions of the pilot projects. However, it was desirable to have a wider range, particularly to reach lower temperature around -10°C. The temperature factor is important for both automation and electrification. Batteries cannot be charged outside of the temperature range, a low temperature would degrade the batteries, a high temperature may generate fire. Sensors, particularly cameras and lidars, do not work well under low temperature, while high temperature is typically not a problem.

Redundancy: Sensors and devices dedicated to automation should be redundant, Lidar-based obstacle detection around the vehicles and secondary cameras for recognition must complement each other to guarantee a fault tolerant system.

Driving in all weather: The bus must be able to drive in common weather, sunny, windy, rainy and snow. The driving in wind parameter was set to a maximum of 55km/h to fit with the standard aerodynamic characteristics of the buses. The snow layer was requested to be 10 cm, and the manufacturers should ensure the vehicle to drive in low friction conditions (icy road). The minimum friction coefficient is 0.2.

3. Operational requirements

Automated and manual mode with onboard remote controller: The bus must be drivable using a steering wheel, a remote controller or other driving equipment. This is a specific legal requirement as the operator must be able to take control over the vehicle.

Operable on fixed routes with but stops: the bus route is set once and for all at the beginning of the robot operation including bus stops. The fixed bus stop can be requested on-demand by passengers from both inside and outside the vehicle (by standing on a bus stop or via mobile app).

Supervision through cellular network (LTE): Speed, location, manual/auto-mode, emergency should be communicated to allow operators to supervise the vehicle from a control room.

Supervision API: The system should be equipped with an API (from the manufacturer or from a 3rd party) to allow the supervision of the system in custom applications such as mobile app for passengers or integration to public transport systems and live-maps. The API should also communicate the current position of the vehicle in real time using GTFS-RT format (General Transit Feed Specification - Reat Time), but also sensors data and camera images from inside and outside the vehicle.

Programmable turn-signals: Turn signal to indicate the turning intention for the autonomous bus before beginning turning and before leaving from the edge of the road (e.g. bus stop). Turn signals to work according to real needs of driving. This must be done according to road traffic legislation.

Data statistic permission: The pilot projects are intended to be used to derive analysis and statistics, hence the manufacturer and the provider should give to the contracting authority full permission to disseminate publicly driving data and statistics. This also includes instant video flow from inside and outside cameras.

Programmable side safety limits: In order to operate safely, and with reasonable velocity in tight spaces, the safety limits must be programmable in terms of front-rear-side distance.

Automatic passenger counter: System to automatically count passengers to be used for statistical purposes.

4. Routes and local requirements for field testing

As the current technological level of automated minibuses for public transportation is still not at the level of driving in any condition, in this section a summary of specifications and limitations will be reported including a comparison between the two most advanced products available in the market (robot buses from Easymile and Navya) which were also piloted in Sohjoa Baltic.

The design of testing routes for robot buses has to consider the current vehicle capabilities. The following list of criteria is based on EasyMile EZ10, robot bus experiences which were used in the SOHJOA-project (2016–2018), driving on three different routes in Espoo, Helsinki and Tampere (Finland) as well as findings from Sohjoa Baltic pilots carried out in Helsinki (Finland), Kongsberg (Norway), Tallinn (Estonia), Gdansk (Poland) and Zemgale (Latvia). This is the current state of the art level, hence it provides the basic framework for route planning for automated shuttle pilots.

Location: If not possible to deploy the bus on a route which complements largely the existing public transport network, cities are likely to see the bus operating in a popular location, where the bus may bring visibility and promote automated solutions in the city. This might be the situation in particular in the case of small scale and short-term pilots.

Real need for mobility: The robot bus can act as a commuter among different modes of transportation, or for example in the internal traffic of campus areas and airports. The bus can carry one safety driver and eight passengers at a time on a public road (around 11 passengers in closed areas and in road traffic if the safety driver has a D class driver's license).

Requirements for the operating area: For safety reasons, the speed limit should be at max 30–40 km/h, so the relative velocity would not grow dangerously high between the bus and other vehicles. Within Sohjoa Baltic pilots the speed of the robot buses were limited to at max 18 km/h or 15 km/h (due to technical and in some cases legal limitations). If the route is shared with faster vehicles, they will need to be able to overtake the robot bus safely. The best situation would be a route free of on-street parking in the area, or if it could be completely banned. If there is on-street parking, the parking area should be clearly marked and the street needs to be wide enough. The robot bus has to be able to move freely along its route as no reliable obstacle overtaking abilities have been yet demonstrated on open streets. All potential distractions. e.g. wrongly parked vehicles disturb the operation of the robot bus, in which case the operator has to take control over the functioning of the bus. It is recommended that the lane would be at least 3,5 meters wide to one direction, because of the required safety distance to potential oncoming vehicles and objects next to the roadside (e.g. vegetation, parked vehicles). The bus may uncomfortably slow down, if the lane is narrower. Usually the bus should not be programmed to run closer than 0.5 m from identified street-side parking areas or fixed objects like roadside vegetation. The bus recognizes these things as obstacles and slows down the pace and eventually stops if an object is too close - this distance may vary case by case. Basically robot buses can handle autonomously different types of intersections (roundabouts, T-junctions etc.) and traffic lights if mounted with specific communication modules, but depending on the difficulty level of an intersection (e.g. amount of traffic, lanes and driving speeds of other vehicles) the bus may need priority in intersections. Priority can be arranged through stop signs or other road signs indicating the right of way as well as (temporary) traffic lights. Alternatively the intersection could be handled by the onboard safety driver or remote operator, but this would not be an ideal situation and emphasizes the importance of understanding the overall robot bus technology and its limitations when planning the route. Weather conditions featuring snow or heavy rain as well as the flying leaves from the trees can cause emergency stops for the robot bus as they are interpreted as obstacles. These factors should be also noticed while planning the route.

Does not interfere with existing public transport: For example in Helsinki, the existing mobility needs are now quite well covered by Helsinki Regional Transport (HSL) buses, trams and metros. Robot buses move considerably slower than existing motorized modes of transport so they can hinder other traffic. In addition it should be considered what additional value a robot bus can provide if operated partly or completely on the same route as regular public transport buses. Though operating on regular routes can allow the use of existing bus stops which can ease the planning and setup of the robot bus route, while it is not necessary to find places (e.g. reserve roadside parking places) and establish bus stops on other places on the route. This may apply especially in case of short term pilots when it is not viable to do laborious and more permanent arrangements. When reserving for instance road side parking places temporarily for the use of robot bus's bus stops, it might be difficult to clearly mark the area and prevent other road users from parking vehicles there. Parked vehicles on robot bus's stops always hinder the operation of the bus and might increase the amount of manual intervention of the onboard safety driver (or remote operator).

The use of pedestrian and bicycle lanes: While planning new routes, it has been discovered that in some cases the use of light traffic lanes or service roads could create new opportunities.. The operating speed of the robot buses used in pilots has been max 18 km/h. Because of that, the bus can be more suitable among pedestrians and cyclists. However, the bus is a size of a minivan, and it takes a significant space of the lane. As a result, it may cause problems with pedestrians and cyclists. Driving the robot bus on a public road requires test plates or other exemption from regular rules of type approved vehicles which have to be granted by the local transportation authority or agency. If the bus operates on a pedestrian road, the road must be marked as a yard street, service road or as another similar which allows driving also for other vehicles. For instance the City of Helsinki has not granted any special permissions to robot buses, so it is not allowed to drive on pedestrian lanes. Cities should think about using the pedestrian and bicycle lanes in terms of what is best suited for the city's own strategy. It should be noted that the use of sufficient wide pedestrian and bicycle traffic lanes can bring new possibilities for routes. However, the bus adjusts its speed to objects moving in front of it, this can make the bus slow down too often on the busy pedestrian streets.

Storage and charging: The bus should be charged where the temperature is above zero Celsius. Charging can be carried out at a normal Schuko socket and the fuse must be at least 16 A. The door of the storage hall should be at least 2.5 m wide and 2.8 m high. Social facilities for the onboard safety drivers and potential a local incident team should be located nearby. Remote control facilities for remote operators could also be located near the route.

Localization of the bus: Usually it is recommended to have relatively large fixed structures (e.g. buildings) at least every 50 m along the route. These structures are used as localization points for the robot bus's navigation. Depending on the satellite coverage it might be also possible to navigate only with enhanced satellite connections (Differential GNSS). So fixed structures would not be needed. Though satellite connection is interrupted in tunnels, also tall buildings and trees next to the route may weaken or generate noise in the signal. In such cases it might be necessary to install some (temporary) fixed structures along the path, e.g some large signs preferably in the shape of a triangle or square (three-dimensional shape).

Stable environment, no construction sites along the path: The map has to be updated, via a path recording procedure and possibly re-program the trajectory to change the position of the path, in case of strong environmental changes during the pilot. It should be found out if such changes (e.g. roadworks or construction of new buildings) will be carried out during the implementation of the pilot and possibly take this into account or plan another route.

5. Safety requirements

The vehicle solution carrying passengers for public transport in urban areas must offer passive and active safety measures that ensure safe traveling. Personal safety for both the passengers, and other people exposed to the vehicle, must be a priority. Furthermore operators and suppliers must show effective safety plans to handle any dangerous scenario.

Along with the pilots' procurement, the consortium has developed an effective list of requirements to fulfil in order to be able to run an autonomous pilot. These information can be shared among stakeholders to serve a starting point for future procurements and city-pilot organization.

System Architecture Plan: A description containing information about each component in the system and how they communicate to each other. Each component should have an individual certification with functional testing.

APIs and communication channels safe and secure by design: Application programming interfaces, open source or proprietary, should be secure by design, meaning that a system verification against cyber attacks is required in each communication channel.

Open interfaces must be separated from safety critical systems: Safety critical systems should comply with ISO26262-"functional specification" and be separated from high level interfaces.

System verification: Verifying that the system has sufficient protection both in the physical and virtual interfaces against cyber attacks, the system should be subjected to a hacking attack by an external company/organisation with proper credentials of such validation methods. Consortiums are also encouraged to set up a bug bounty system and subjecting the system to a hackathon-type of hacking event. Remote operation and fleet management systems must pass external validation for cyber safety by guidelines of National Cyber Security Authorities

System Architecture documents need to be verified by a 3rd party validator: Providers should provide evidence of software verification by a 3rd party validator. The validation must include privacy setting and use of private/public data acquired from cameras and sensors on the vehicle in compliance with the new GDPR European law. It should also include a risk assessment strategy and data deletion plan. AI-related models must be compliant with the Algorithmic Accountability Act of 2019.

Safety Plan & Risk Assessment: Any mission-critical systems must be provided with a safety plan and a risk assessment report. The general rule is that redundancy is required to ensure fault-tolerance in autonomous vehicles, and particularly for safety and mission-critical components. The risk analysis must include different problematic scenarios (for instance GPS connection loss, cellular connection connection loss, cyber attacks, vandalism etc.). A contingency plan to take into account unpredictable events must also be provided including system-failure plans for each subsystem. The plan must include a specific risk assessment for fire and electric components, a risk analysis for occupational hazards for operators (both onboard and remotely) to include for instance work with high-voltage/current, chemical in batteries, risk of injury etc.. The plan must also include the safety guidelines to be given to operators for emergency services, including necessary training.

Safety Plan & Risk Assessment verified by an independent safety assessor: The documentation previously indicated should be validated by a 3rd party independent assessor to ensure that the risks are correctly taken into account and minimized.

Accidents & Incidents management plan: Providers need to have an accidents & incidents management plan devised in case of unforeseen circumstances (this may be together with the safety plan & risk assessment).

Crisis Communication Plan: Crisis Communication Plan should be devised, with clear Chains of Command & Communication that will be followed should the situation arise

Fire extinguishers and first aid kits in vehicle units: Fire extinguishers and first aid kits must be available for each vehicle unit. They must be easily accessible by passengers and the operator in the vehicle.

System must fulfill the European standards for Electro-magnetic compatibility (EMC): The vehicles must comply with the electro-magnetic compatibility (EMC) Directive 2014/30/EU that ensures that electrical and electronic equipment does not generate, or is not affected by, electromagnetic disturbance.

IV. Conclusions

In conclusion this document provided an overview of the technical specification and requirements for autonomous driving in urban areas. From the application of the current technology during the pilot projects some criticalities emerged demonstrating the current limitations of the vehicles, for instance energy efficiency and automation level lower than expected. These challenges can be overcome and these pilot projects have provided useful information for developers and stakeholders to move forward with the activities. Among the studies performed during the project the weather-related risks for autonomous driving and energy minimization through speed profiling optimization are considered as important for the development of the field.

From a safety perspective, it is reasonable that the risk assessment must be as high as possible, though unexpected accidents may occur and this risk should not stop vehicle automation. From a business perspective such risk is currently feasible with the help of a stable regulation defining liability and insurance for providers, manufacturers and operators.

V. References

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