Automated vehicle traffic control tower - the bridge to next level automation

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Abstract

Automated vehicles (AVs) have the potential to enhance road capacity, improving road safety and traffic efficiency, and research and development on AVs has been going on for many years. However, AVs fail to make decisions on contradicting situations, and are not able to have control in all conditions due to highly dynamic driving scenarios, when the complicated traffic rules and real situations interacted. This limits their usage and the potential benefits that they can bring. Furthermore, regulations, infrastructure development, and public acceptance cannot keep up on the same pace as technology breakthroughs. Facing these challenges, this paper proposes automated vehicle traffic control tower (AVTCT) acting as a safe, efficient and integrated solution for automated vehicle control. It introduces a novel concept of AVTCT for control, management, decision-making, communication and interact with various aspects in transportation. AVTCT has the potential to overcome the control challenges with AV and reach the potential with AV. Possible functionalities and benefits of AVTCT as well as challenges are discussed, which set the foundation for conceptual model, simulation and real application of AVTCT.

Keywords: Remote control, automated vehicle, automation level, control tower, safety, transport efficiency

I. Introduction

Automated vehicles have shown the potential to enhance road capacity, improve road safety, increase transportation efficiency, and decrease traffic congestion and fuel economy (Dickmanns 1988; Bagloee et al., 2016; Chen et al., 2017; Sanaullah et al., 2017). However, despite many promising advantages, it is unlikely that automated driving system are going to be able to deal with all conditions, at least in the near future: driving scenarios are complex and not always predictable. Failures are anticipated e.g. in situations that are not observed before, or when the automated driving systems (ADS) system is confused by conflicting information from its sensors. Currently, the focus of ADS is on the vehicle itself, and solely assure safety (Kang et al., 2018). Solutions for control failures are either return to human driving or stop the vehicle. Using a human driver on-board or an emergency stop as fallback is inefficient, costly and could be unsafe. Furthermore, it is not applicable for the commercial mobility services with fleets of shared taxis that are expected and part of the widespread vision (Fagnant et al., 2015; Ohnemus & Perl, 2016). High accessibility, uptime, optimal fleet utilization, and fleet management on a system level is fundamental for these services. These commercial services are realized by the fact that the vehicles are capable to fulfill their transportation tasks without the intervention of an on-board driver.
It is crucial to view the ADS from a new perspective regarding efficient, economic and safe control given each SAE automation level actually depends on the driving scenarios; the critical distinctions are whether to have human driver in the loop in the dynamic driving tasks (SAE J3016). Currently, AVs make decisions based on the perception of the environment and predefined situations on conditional scenarios (Pendleton et al., 2017). When complicated traffic rules and real situations dynamically interact, as e.g. in road constructions, accident zones, bad weather conditions, and traffic light malfunctions, it is not enough to follow a predefined control, let alone making decisions on contradicting information. Nevertheless, it is impractical and infeasible to have a human in each AV to be ready to take control, especially in commercial services such as shared taxi services. What’s more, fleet management and optimizing the utilization of the fleet are important tasks for commercial services. It leads to the query of how AV in commercial services can be controlled in the dynamic driving scenarios, given the current stage of technology, infrastructure, policy, business model and user acceptance.

It is inspiring to learn from the idea of having control towers on air traffic control and management. The aviation industry has fully embraced automation in flight control and navigation systems since the mid-1970’s (EE Times, 2016). In the beginning, control towers mainly served in coordinating among airports and aircrafts, controlling flying courses, and directing taking off and landing. When the autopilot mode is enabled, control towers monitor and control the aircrafts remotely from the ground. Nowadays, with the development of communication technologies, cloud solutions and digitalization, the air traffic control towers are developing to be remotely located to further improve safety and efficiency. Compared to on-road automated driving, the aircraft autopilot systems are more mature and have integrated into the operation routine in the aviation domain for many years. Despite the maturity in the aviation control, the control tower is still central in safety and efficiency operation, and is not replaceable (Manske & Schier, 2015; Gawade & Zhang, 2016). Given the current development status of automated vehicles, can a remote traffic control tower (TCT) improve the safety, service and operation of automated road vehicles?

In practice and early trials there are several vehicle developers that are exploring opportunities with remote control towers for automated road vehicles. Nissan\(^1\) announced that they plan to have a human remotely in a call center for their automated driving vehicles at the Consumer Electronics Show 2017. The purpose is that when cars send out an emergency signal,

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\(^1\) [https://www.wired.com/story/phantom-teleops/](https://www.wired.com/story/phantom-teleops/) accessed 2018-11-30
instead of taking over the driving, human operators in the call center will use the car’s sensors to look around, determine the best course of action, and issue fresh instructions to the computer onboard the car. For example, a digital path can be drawn and transmitted to the car for execution, remaining in automated mode all the while. The machine learning system can store the problem and the human-derived solution, which helps the vehicle perform better next time.

Phantom Auto\textsuperscript{2} plans to establish call centers where a few humans will oversee a fleet of automated cars. If the onboard control of an AV has failures, a human operator utilizes the car’s cameras and microphone to perceive the situation and a steering wheel and pedal combo in the call center to control the vehicle. Starsky Robotics\textsuperscript{3}, a san Francisco based start-up developed an automation system that allows trucks to self-drive in simple highway conditions but has a human ready to take control remotely, when it’s time to rumble down tricky city streets. Waymo’s cars by Google, which are already roaming Arizona with no one inside, will be able to ask humans in a remote call center for help (Waymo, 2017). Uber and Toyota also has certain remote operation of automated vehicle in unexpected environment according to Wired (2017)\textsuperscript{4}.

However, the pioneering attempts mentioned above only link with their own product development and promotion. The research on what means are necessary for automated vehicle traffic control tower (AVTCT) to centrally support operations, management and control of automated vehicles, especially with regard to fleets of automated vehicles, is still scarce. Although Kang et al. (2018) pointed out the necessity of augmenting self-driving with remote control, the discussion was mainly from a technical perspective instead of providing a general conceptual model of control tower. It is necessary to understand the potential functions and benefits of AVTCTs and investigate how they can be integrated with the technical aspects, human factors, situation awareness, and policies on national, regional, manufacturer and fleet levels. This paper aims to examine the following questions:

Q1. What can be learnt about AVTCT from the current ADS and the use of traffic control tower in the aviation and railway domains?

Q2. What are the required functionalities and roles of AVTCT?

Q3. What opportunities and challenges can AVTCT provide to increase safety and efficiency of AV fleet management and commercial services?

\textsuperscript{2} https://phantom.auto/press/ accessed 2018-11-30
\textsuperscript{3} http://starsky.io/ accessed 2018-11-30
The following part of the paper is structured in four sections: In Section II, a review of current literature on ADS is presented. Some of the methods for their design are presented to find the answer for Q1. In section III the possible functionalities that are needed in remotely controlling automated driving is discussed to get leads for Q2. This section also lists the open questions of AVTCT based on expert workshops to find potential answers for Q3. Section IV concludes with remarks on the state of the art and potential areas for future research.

II. Literature review

The search for literature is conducted by using Google Scholar and Scopus, with the key words “automated vehicle control” in the title, abstract and keywords. Literature from year 2013 or later were searched since NHTSA issued their automation level in 2013 (NHTSA, 2013) and then SAE issued their standards for automation in 2014 and updated them in 2016 (SAE, J3016). The search gave 580 matches, in which many were discarded because their focus was not on control. The keywords “driverless vehicle control” combined with either “control AND management”, “traffic remote control”, “traffic control tower” or “traffic control center” were then applied, and the match downsized to 70 papers. A summary of these papers supports answering Q1 are summarized in the following part of this section. The findings in the literature are divided into three areas. First, functionality of ADS systems to give an understanding of the needs and challenges related to automated driving. Second, how traffic control towers are used in other transport modes to identify best practices. Finally, human factors aspects related to automated driving, as the interaction between the ADS and the human is crucial for safe and effective driving.

2.1 Three functionalities in the current ADS

The functionality of an automated vehicle is based on a complex automated driving system (ADS). Three of the main tasks for the ADS are perception, plan and communication and control (Amer et al., 2017; Pendleton et al., 2017; Kang et al., 2018).

2.1.1 Perception

Perception means that an ADS is able to collect information and extract knowledge about the environment by using internal and external sensing. Internal sensing is essentially to observe the states of current sensors, switches, and actuators, which are mainly used for self-diagnosis (inertial position, velocity, attitude, rates). The external sensing includes estimation of the current location, map features, and dynamic objects, which are used for localization, mapping, and obstacle detection (Andersen et al., 2017). The perception task includes creating usable
information about the vehicle and its environment (Campbell et al., 2010). The perception task also includes identification of lane boundaries, traffic lights and road signs to provide input for path planning and speed control. Challenges in perception include accurately positioning the vehicle, precisely detecting signs, and obstacles that make it difficult to sense the surrounding environment (Zheng et al., 2015; Kang et al., 2018). Sensor information rely on real circumstances and they have limitations in perceiving real time raw data (Liu et al., 2016; Amer et al., 2016).

Perception challenges are countered by the following technological solutions, sensor systems with GPS, cameras, radar or laser range finder, and advanced automated driving algorithms are employed (Zheng et al., 2015). AVs are ultimate electronic devices on wheels that track localization, detect surroundings and perceive real time data. For example, light detection and ranging, wide range of sensors and microprocessors, cyber-physical modules, in-vehicle communication networks, and several hundred megabytes of software are equipped in an AV (Ray et al., 2017; Zhu et al., 2017). The perception functionality prepares for realizing a better plan functionality (Bagloee et al., 2016; Tummala et al., 2016).

2.1.2 Plan and Communication

Plan means that the AV sets the optimal route from one location to another while following traffic rules as well as avoiding obstacles detected by the perception functionality. Plan in ADS is usually performed in a hierarchical manner consisting mission plan, route plan, behavior plan and motion plan (Andersen et al 2017).

It is crucial for AVs to have effective communication internally and externally to fulfill the planning task. In particular, this is true for mission planning, which generally is performed through graph search over road/path network connectivity (Andersen et al 2017). Advancement in wireless communication technologies and vehicular networks are expected to boost the development of automated driving and employ the Vehicle-to-Everything (V2X) communication (Lu et al., 2014; Zheng et al., 2015; Coppola & Morisio, 2016). Current studies show that V2X communication can contribute in improving road safety, availability of infotainment services and the efficiency of transportation systems (Kumar et al., 2013; Tuohy et al., 2015; Ucar et al., 2016; Chen et al., 2017; Ashraf et al., 2017).

Connected vehicle technology can provide real-time information about the surrounding situations, improve decision efficiency and enhance safety and mobility. This also enables behavioral plan that is decision making to ensure the vehicle follows any stipulated road rules
and interacts with other agents in a conventional, safe manner while making incremental progress along the mission plan’s prescribed route (Talebpour et al., 2016). The Fifth Generation (5G) wireless communication systems is a promising solution enabling effective communication for connected AVs (Bierstedt et al., 2014; Di Taranto et al., 2014; Zheng et al., 2015; Kong et al., 2017; Ericsson, 2018).

Through perception and communication, AVs conduct mission planning to decide a sequence of actions to reach a specified goal. Mission planning chooses the optimal route, avoids unsafe situations and ready to conduct travel behavior due to mission requirements, which all leaves to the next task: to execute the planned actions (Latombe, 2012).

2.1.3 Controlling

AVs should follow predefined traffic rules and scenarios, such as drive within a lane, stop at the red traffic light, give way to pedestrians, and so on. To do this, the AVs are equipped with motion control for longitudinal and lateral path control and actuation in steering and braking control (Vahidi & Eskandarian, 2003). In case of any emergencies, an emergency function will be enabled and stop the vehicle appropriately and/or hand over to a human. So far, this emergency procedure is the only way in dealing with the situation (Khodayari et al., 2010; Amer et al., 2016). Although combining with current sensor and communication technologies, the intelligence level to recognize sudden changes and react accordingly is still not reached (Kang et al., 2018).

The success of control is highly dependent on the success in perception and plan. Even the leaders in AVs development, like Google, Tesla, Uber, have all reported accidents in automated driving (Higgins, 2016; Watts, 2016; Singhvi & Russell, 2016). Schoettle and Sivak (2015) conducted a preliminary analysis and showed that, comparing to conventional vehicles, automated vehicles have a higher crash rate and injuries per million miles traveled. They also showed that AVs could not be blamed for the accidents, as they have perceived and planned to follow the traffic rules. Instead, failures are due to the appearance of new scenarios in which even emergency stops are dangerous.

Apart from the technical control failure, AVs face other issues in control. First, the current control technology is still unable to correctly detect and identify objects in typical transport scenarios like pedestrians crossing streets without obeying rules and temporary construction workers (Nikitas et al., 2017). Second, users are skeptical to accept that automated vehicles take over driving and control, and the universal acceptance of such a transition is not guaranteed or
Third, current road transport infrastructure cannot fully support the driving environment that AVs require. Especially mixed traffic situations, where connected AVs share road space with partially automated and conventional man-driven vehicles, could create conflicting problems (Nikitas et al., 2017).

According to SAE (2016), Level 5 automation allows the driver to be out-of-the-loop. The ADS takes care of all control activities, and a human driver is not needed anymore. However, several problems, such as limitations of technology, divergent public acceptance, liability issues, and human-machine ethics, are yet to be solved before Level 5 of fully automated driving can become publicly available at a wide scale (Kyriakidis et al., 2015; Lu et al., 2016). According to Nissan’s R&D director Maarten Sierhuis on Wired (2017)⁵, the truly driverless car is an unreachable goal within five years or less, human will most likely be needed in the loop one way or another.

2.2 Control in other transport modes

Air traffic control (AiTC) gives guidance to aircrafts, prevents collisions, and manages safe and orderly traffic flow. It is a vast network of people and equipment that ensures safe operation of aircrafts (Ahmad & Saxena, 2008). AiTC have controllers for terminals and routes (Pierce et al. 2016). Controllers for terminals organize the air traffic flow in and out of airports, and route controllers ensure the safe separation and orderly flow of aircraft both above and outside of airspace surrounding airport areas. In the air traffic control system, control towers play an important role for maintaining safety and managing the traffic (Schmidt et al., 2009).

Traditionally, each airport is equipped with a control tower. The tower provides visual surveillance mainly through the controller’s out-the-window (OTW) view of the airport surface and local airspace. All surveillance and communications information are transmitted to one or more controllers in the tower (Reason Foundation, 2016). However, the advanced electronic surveillance system, including development, operation and maintenance, AiTC generates very high costs. Remote air traffic control (RAiTC), utilizing the advancements in cloud computation and communication technologies, has been proposed to reduce the costs. RAiTC has been developed in many countries like Sweden, USA, UK through programs as SESAR, Vision 2020 or NextGen (Schmidt et al., 2009). It shows that the RAiTC not only can decrease the up-front cost, but also can increase the safety and efficiency in facilitating autopilot motion of the aircraft in route control (Fürstenau et al., 2009; Gawade & Zhang, 2016).

Not only in aviation, but also in marine and railway automation driving, remote control through a control station or control center has shown its importance in navigating, guiding and controlling the corresponding vehicle. In railway control, focus is mainly on ensuring safety, regularity, reliability of service and punctuality of operations (D'Ariano, 2009). The train traffic control system aims at being able to handle more frequent traffic, higher speeds and several different companies operating on the infrastructure (Kauppi, 2006). In unmanned marine vehicles, remote control is mainly for guidance, safety and increase task efficiency (Campbell et al., 2012; Liu et al., 2016). No matter in which kind of transport, the need of remote control is due to the failure of vehicles in having correct situation awareness and poor human machine interfaces (Fürstenau et al., 2009; Heape, 2012; Dadashi et al., 2014).

The main difference between automated on-road driving and automated (air, railway, and water) driving is the intensive road network and complex infrastructure. The concerns in human factors and situation awareness are different in the different transport modes. To answer the questions raised in the introduction of this paper, the focus in next section is on those concerns related to on-road automate vehicles.

2.3 Human factors in on-road automate vehicles

Current studies on human factors indicates that automation resolves the imprecision and variability of human task performance, but also yields new types of safety concerns (Lu et al., 2016). Moreover, Workload and situation awareness are two of the most important human factors that influence performance and safety (De Winter et al., 2014). A high level of automation can cause out-of-the-loop problems such as complacency, skill degradation, mental underload (when the automation functions reliably), mental overload (when the operator suddenly needs to solve an automation-induced problem), and loss of situation awareness (Bainbridge, 1983; Endsley & Kiris, 1995; Parasuraman & Riley, 1997; Hancock et al., 2013; Vlakveld, 2015, Young & Stanton, 2007; Seppelt & Victor, 2016).

Casner et al. (2016) argued that intermediate levels of automated driving, where human is expected to monitor, may be particularly hazardous because humans are unable to remain vigilant for prolonged periods of time. Therefore, due to the changes in the driver’s role in automated vehicles compared to manually driven vehicles, human factors need to be carefully considered by researchers, designers, and policy makers (Merat & Lee, 2012; Merat et al., 2014; De Winter et al., 2014; Lu et al., 2016). “Taking over control” is a primary task left for the human operator who supervises an automated system. A fact that cannot be ignored is that
automated driving systems will occasionally fail, and human has to resume control to for safety (Bainbridge, 1983; Goodall, 2014).

Seppelt and Victor (2016) point out that human factors also should be dynamically considered depending on the automation level. According to SAE (2016), in Level 2 automation, human is still required to participate in the dynamic driving task by monitoring the driving environment and by providing fallback performance of the dynamic driving task. The dynamic driving task “includes the operational (steering, braking, accelerating, monitoring the vehicle and roadway) and tactical (responding to events, determining when to change lanes, turn, use signals, etc.) aspects of the driving task, but not the strategic (determining destinations and waypoints) aspect of the driving task” as is stated in SAE (2016).

In SAE Level 3, the human is not required to monitor the driving environment but is expected to respond appropriately to a request to intervene, as a fallback to perform the dynamic driving task. In contrast, in SAE Level 4 the responsibility for safe operation lies solely on the vehicle, and the system should not be designed to rely on the driver as a fallback. The key human factor challenges in automation is that it is a cost-benefit trade-off, where reduced human performance is a cost and increased vehicle performance is a benefit. The better the automation, the less attention drivers will pay to traffic and the system, and the less capable they will be to resume control, the driver may not provide suitable fallback performance of the dynamic driving task (Seppelt & Victor, 2016).

Attention has been drawn to study key performance indicators (KPI) in response time of humans to automated driving system failures (Merat et al., 2012; Strand et al., 2014; Melcher et al., 2015; Zeeb et al., 2015). For example, complacency (Parasuraman & Manzey, 2010), mental workload (Martens & Beukel, 2013; De Winter et al., 2014) and situation awareness (Endsley, 1998; Kaber & Endsley, 2004; De Winter et al., 2014; Endsley, 2017) have been studied. These studies are based on the current automation level, where human factors influencing on-board control are studied. The human factors in remote control, however, are still rarely studied.

To conclude Section 2 and answer Q1, current ADS literature have mainly focused on technological aspects, especially in the control stage. Research has primarily focused on development of on-board systems and on the human as an on-board fallback system. At the beginning of the development of automated vehicle, there are challenges for ADS to reach the full potentials.
III. A new perspective for automated vehicle traffic control

In the search for literature about automated vehicle control, only a few studies with focus on remote perception, plan, monitor and control for on-road automated vehicles were found. Remote control systems can act as an economic and safety backup of automated systems (Kang et al., 2018). In remote control, one person can manage multiple automated vehicles, take actions upon request, and take over the control after system failures (Waymo, 2017). Inspired by the control tower in aviation control, automated vehicle traffic control tower can be a potential solution to control and manage automated vehicles in various scenarios. It should be noted that remote control from a control tower is not the same as remote driving of the vehicle.

A control tower is a part of the system despite that automation has been in place for a long time in other transport modes. For on-road automated vehicles, the situations will be even more complicated. Control tower could therefore be a solution to integrate vehicle, human and dynamic situations to fulfill real transport assignments in an efficient, safe and reliable way. In the control tower, human operators are prepared when necessary support is needed. AVTCT perform the traffic control from a holistic level to a specific individual level for fleet management, commercial services and personal travel.

3.1 The role of AVTCT

An AVTCT has the potential to control vehicles when the ADS control fails. The ADS could be a single vehicle or a fleet, and should have a holistic view of the situation including e.g. weather data, traffic information, and movements on other vehicles. Decision-making can then be more proactive, reactive and responsive because information is processed more efficiently. Cooperation among stakeholders and support both from technical side and policy side can be conducted through AVTCT. AVTCT does not only serve as a safety control center but also as a platform for handling requirements from various actors and make the whole transport system more efficient and intelligent. Figure 1 illustrates how AVTCT interacts with automated vehicles.
AVTCT may provide various functions when it comes to fleet management and autonomous driving, in the following, three potential roles of AVTCT are explained. First, similar to AiTC, one potential role of AVTCT is to assure traffic safety and increase traffic efficiency due to its potential in dealing with dynamic situations. Second, AVTCT can probably make decisions and take actions to achieve safe, reliable and efficient automated driving in teleoperation mode. This is not only due to a comprehensive hardware composition in AVTCT but also due to a consideration of influence from human factors and human machine interactions. Third, AVTCT could coordinate among different fleets, infrastructures, service providers and traditional road users. What’s more, having AVTCT facilitating the ADS and integrating other aspects in the transport system can bring great potential to improve uptime and service accessibility, enhance fleet management, promote shared mobility services and optimize fleet utilization on a system level. Table 1 further explains the detailed potential of AVTCT in solving the main challenges in ADS.

Table 1: Challenges in ADS and potentials in AVTCT

<table>
<thead>
<tr>
<th>Challenges in ADS</th>
<th>Potentials in AVTCT</th>
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<tbody>
<tr>
<td>Accurately sense the surrounding environment.</td>
<td>Complement the on-vehicle sensor system with external real-time traffic watch and processed cloud information.</td>
</tr>
<tr>
<td>Unable to recognize sudden changes and react accordingly.</td>
<td>Ability to process dynamic scenarios and react accordingly with intervention of human operator if required.</td>
</tr>
<tr>
<td>Inefficient and potentially dangerous solution of emergency stop.</td>
<td>Take safe and efficient control actions according to the real situation.</td>
</tr>
<tr>
<td>Advantage</td>
<td>Disadvantage</td>
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<td>-----------</td>
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</tr>
<tr>
<td>Can manage multiple vehicles at the same time.</td>
<td>Control only limited to one vehicle that is inefficient.</td>
</tr>
<tr>
<td>Enable the cooperation among stakeholders and vehicle brands for optimal control and management.</td>
<td>Control and management restricted to only one manufacturer, which is costly.</td>
</tr>
<tr>
<td>High potential to gain user acceptance and compliance as well as policy support.</td>
<td>Low user trust and high difficulty to get policy ready.</td>
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### 3.2 Areas of challenges in setting up AVTCT

AVTCT integrates various aspects of automated driving, and it can facilitate for decision makers and decision support systems to make safer and more efficient decisions in dynamic driving scenarios. However, the concept of AVTCT has not been discussed before in literature and there are still many considerations and challenges in configuring the conceptual framework to set up AVTCT.

![Figure 2: Aspects to be considered in setting AVTCT](image)

In order to set up an AVTCT, many aspects need to be taken into consideration. First, the identification of technical solutions to effectively enable the transfer of critical information to and from the AVTCT. Second, representation of real time traffic information to the human controllers in the AVTCT. Third, providing relevant and novel abstractions, visualizations and interaction modalities, thus supporting advanced decision-making capabilities. The areas of
considerations speak to: human factors, human machine interactions, connectivity and information optimization, operation and control of vehicle fleets, remote operation.

These aspects is also reflected in the different levels of abstractions considered in the definition of features and functionalities for the future AVTCT entity. At “Macro” level, the TCT will act as a cluster-head information node, capturing the global state of the traffic network and providing monitoring and control capabilities influencing the behavior of the network as a whole. At “Micro” abstraction level, the TCT will be required to support real time control and monitoring information flows with each of the individual vehicles. The areas of consideration are summarized and illustrated in Figure 2. These aforementioned aspects revealed several design and operational challenges.

3.2.1 Design challenges of AVTCT

First, to address challenges related to human factors and human machine interaction, several questions need to be answered. For example: what actor should operate the AVTCT? What situation reaction time is required by a human operator in the case of decision to take over an AV? When should the human operator in the AVTCT trust the ADS when it comes to providing alternative plans or choose one that the operator thinks is the safest and most applicable? How can the AV learn from the human operator, by combining data from situations with the operator’s actions? If so, at which stage can the operator be confident that the AV has learned to handle situations that it failed previously?

Second, for connectivity and information optimization, the network infrastructure and communication protocol needs to be set to bound the latency between the remote human drivers and the vehicles (Kang et al., 2018). However, the protocols in V2X communications are not the same, and it will be challenging to ensure Quality of Service (QoS) for communication under different protocols. Key questions that need to be considered are: How to ensure QoS given the current LTE6 networks and optimize the data transmission under different protocols and standards (Huang et al., 2013; Gerla et al., 2014; Seo et al., 2016)? How should the future 5G networks be used to ensure the low latency and high bandwidth communication required for automated vehicles (Zhang et al., 2014; Di Taranto et al., 2014; Vlachos et al., 2017)? What if there is an automated vehicle that is not connected to the control tower? Due to high mobility and the dynamic change of the communication network topology, it is difficult to provide

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6 LTE (Long-Term Evolution) is a standard for high-speed 4G wireless communication for mobile devices and data terminals.
satisfactory services only through a single wireless access network. How should different network providers work together to enable efficient communication between AVTCT and AVs in real traffic (Mir& Filali, 2014; Campolo et al., 2017)?

Third, in remote operation, low latency and accuracy are crucial, for both single vehicles and fleets. Remote operation means that control and management of AVs is performed from AVTCT. It can be support for the vehicle to function, new commands for the vehicle to take action in dynamic scenarios and remote driving when it is necessary. Image sensing, 3D map, vision could be delayed in the transmission, this could lead to decisions made in AVTCT already be too late. Although Nissan published that their remote control approach can avoid the latency problem, even works when cell connections are weak. Kang et al. (2018) pointed out that the remote response center should be selected and/or switched based on the maximum end-to-end latency. The main reason is that in denser areas with many vehicles or during road constructions, this function will be more practical as system failures are more likely to occur. However, this is still not tested in other cases and may not applicable to AVTCT. For remote operation, large volume of data needs to be transferred between the vehicle and the AVTCT. This leads to several questions: In order to provide sufficient and instantaneous information from the AV to the AVTCT, real time streaming Which information is needed when and at what resolution? How can data be filtered and compressed? What type and structure of data?

Fourth, technology is developing much faster than infrastructure, regulations, and policies. The unbalanced stage from the whole transport system is becoming more and more obvious. This leads to questions such as: How should remote operation be conducted when the stakeholders have different requirements? Should the fleet management and commercial service be separated from the personal traffic due to the variations on the target user, capacity and different requirements on road infrastructure? How should the data be stored and shared to improve the transport system? How is the functionality of the AVTCT limited by current policies and regulations, and how should policies and regulations be changed to support the functionality of the AVTCT?

3.2.2 Operational challenges of AVTCT

To explore the challenges and uncertainties related to operating AVTCT, opinions from the AV OEMs spectrum, the authority spectrum and the communication technology spectrum were gathered by inviting 42 experts through 3 workshops within the prestudy of AVTCT project. Table 2 summarizes the operational uncertainties for AVTCT identified by the experts. In Table
2, the challenges are also prioritized based on the input from the experts and categorized based on their operational uncertainty. The high operational uncertainties identified and presented in Table 2 are at a holistic level.

### Table 2: Operational challenges for AVTCT

<table>
<thead>
<tr>
<th>Operational challenges</th>
<th>Description</th>
<th>Priority level</th>
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<tbody>
<tr>
<td>Ownership of AVTCT is not decided</td>
<td>These uncertainties have the high priority as they are fundamental for the design of the AVTCT</td>
<td>High</td>
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<tr>
<td>Architecture of systems of AVTCT and respective roles in different implementation and on different level is unclear.</td>
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<td>Contexts and conditions for AVTCT is unclear</td>
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<td>Level of authority for AVTCT is uncertain</td>
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<tr>
<td>Levels of vehicle automation and the required control are dynamic</td>
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<td>Efficiency requirements on AVTCT are unclear</td>
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<tr>
<td>No standardization of sensor suite</td>
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<tr>
<td>Different requirements of infrastructures in mixed traffic</td>
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<tr>
<td>Requirements on type and quality of data</td>
<td>The medium operational uncertainties are mainly related to connection issues, human factor influences and quality controls. As there are experiences from aviation and railroad that can be learned, uncertainty level is regarded as medium</td>
<td>Medium</td>
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<tr>
<td>User group, service requirements and charge for the AVTCT services</td>
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<td>Security of vehicles and AVTCT</td>
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<td>Level of situation awareness</td>
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<td>Level of immersion and comprehension</td>
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<td>Reliability of connection to the vehicle</td>
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<td>Laws allowing remote control of multiple vehicles</td>
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<td>Quantification of the value of AVTCT</td>
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<tr>
<td>Handling of technical failures</td>
<td>The low operational uncertainties is mainly related to the vehicle and passenger details. These uncertainties are not crucial to start the design and test of AVTCT.</td>
<td>Low</td>
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<td>Cost and effectiveness compared to on-board drivers</td>
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<td>Communication to passengers</td>
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<td>Passenger trust</td>
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<td>Digital limitations of real time traffic</td>
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<td>Size and speed of the vehicle</td>
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</table>

The ownership of AVTCT, the architecture of systems of AVTCT and respective roles in different implementation and on different level is unclear. The contexts and conditions for AVTCT, the level of authority in charge and levels of vehicle automation and the required
control are dynamic. These uncertainties should have the high priority as they are fundamental for the design of the AVTCT.

The medium operational uncertainties are mainly related to connection issues, human factor influences and quality controls. The requirements on data architecture, security issues, and connection reliability are important for communication between AVTCT and AVs. The user groups and service requirements, regulations and laws on remoting control influence the operational width and depth of AVTCT. As there are experiences from aviation and railroad that can be learned, uncertainty level is regarded as medium.

For the low operational uncertainties, it is mainly related to the vehicle and passenger details. The cost and effectiveness compared to on-board drivers is unclear, passengers’ trust on AVTCT and digital limitation of the traffic information influence the implementation of AVTCT. These uncertainties are considered as low because these are not crucial to start the design and test of AVTCT. However, to reach successful design and implementation of AVTCT in the long term the uncertainties on all priority levels need to be considered.

IV. Conclusion

This paper introduces the concepts of using automated vehicle traffic control towers (AVTCT) as a solution to facilitate automated vehicles (AVs) and to reach to the full potentials of AVs in the current automation level. AVTCT has the potential to be the bridge to achieve advantages of AVs even before technology is mature enough to reach to the next automation level. The studies on the use of traffic control towers in air and sea traffic helps on forging the AVTCT concept. Besides the expected benefits of AVTCT presented in this paper, the operational uncertainties of implementing AVTCT in real scenarios are also analyzed based on workshops with experts. The main design and operational challenges of AVTCT have been presented and prioritized.

Automated Vehicles (AVs) have many promising advantages, such as enhancing road capacity, improving road safety and traffic efficiency. However, to utilize the full potential of AVs, the vehicles need to be able to operate in all conditions. This introduces three main challenges. First, the driving scenarios are highly dynamic and not always predictable. Developing AV’s to be able to make decisions in contradicting situations is a major hurdle on the road towards fully driverless vehicles. Second, technologies that support automated vehicle control need time to develop to achieve the level of reliability needed to ensure safety. Third, regulations,
infrastructures, public acceptance cannot keep up on the same pace as technology breakthrough for AV control. Nevertheless, it is unfeasible and too costly to have a human in each AV ready to take control, especially in fleet management, commercial services and shared mobility services. These challenges are open development areas to unlock the potential of AVTCT.

Upon maturity, the automated vehicle traffic control tower (AVTCT) can act as an economic and safe backup of automated systems. Remote control from AVTCT can have responsive, proactive and reactive decision-making. The micro-macro management can be integrated. Predications and plans for active response can be reached for dynamic changes. It is crucial to solve the automated vehicle control failures from a new perspective by introducing traffic control tower to remotely control and manage automated vehicles. The development of AVs will continuously face new challenges, but when AVTCT reaches its potential, it may play a critical role on multiple levels for AVs control.

In AVTCT, one human operator can manage multiple automated vehicles, take actions upon request, and take over the control after system failures. One potential role of AVTCT is assuring the traffic safety and increase traffic efficiency. Another role could be coordinating among the fleets, infrastructures, service providers and traditional road users. AVTCT can act as a decision maker and can also be a decision support system for automated vehicles in dynamic driving scenarios. Although control tower has been widely applied in aviation, marine and railway. The context between automated on-road driving and automated driving in the air, on railway and in the water are different. The AVs need road network and get more complicated interactions with surroundings infrastructure. The scale that AVs cover in transport is also broader and more complex than those aforementioned transportation modes. It is therefore novel to introduce the method of AVTCT for operate and control AV. Furthermore, it is necessary to test possible functionalities and benefits of AVTCT, as well as reveal challenges and find answers for open questions in designing and operating AVTCT.

To design and make AVTCT operational, the highest operational uncertainties, such as the ownership of AVTCT, the architecture of systems of AVTCT, need to be prioritized and answered. The possible economic impacts need to be investigated to see how AVTCT can help to optimize the vehicle utilization and to reduce energy use. Gathering perspectives from industries, business, authorities and users is necessary. A demonstration model should be set up in order to apply the architecture framework and possible business models that come along the
adoption of AVTCT. System effects that will be brought by AVTCT are also a focus for future work.

There are many open questions for designing and operating control towers for automated road vehicles, but with the knowledge from control tower in other transportation modes, the development of technology and the support from different spectrums, automated vehicle traffic control tower is the bridge to next level automation.

IV. References


63. NHTSA (2013) US department of transportation policy on automated vehicle development, p 4


