Automated Vehicle Traffic Control Tower: A Solution to Support the Next Level Automation

Xiaoyun Zhao, Rami Darwish, Anna Pernestål

Abstract—Automated vehicles (AVs) have the potential to enhance road capacity, improving road safety and traffic efficiency. Research and development on AVs have been going on for many years. However, when the complicated traffic rules and real situations interacted, AVs fail to make decisions on contradicting situations, and are not able to have control in all conditions due to highly dynamic driving scenarios. This limits AVs' usage and restricts the full potential benefits that they can bring. Furthermore, regulations, infrastructure development, and public acceptance cannot keep up at 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 AV control. It introduces a concept of AVTCT for control, management, decision-making, communication and interaction with various aspects in transportation. With the prototype demonstrations and simulations, AVTCT has the potential to overcome the control challenges with AVs and can facilitate AV reaching their full potential. Possible functionalities, benefits as well as challenges of AVTCT are discussed, which set the foundation for the conceptual model, simulation and real application of AVTCT.

Keywords—Automated vehicle, connectivity and automation, intelligent transport system, traffic control, traffic safety.

I. INTRODUCTION

AVs are on the development of the technological front since they may provide potential benefits for both freight and people transportation. AVs have actually shown some of the potentials in enhancing road capacity, improve road safety, increase transportation efficiency, and decrease traffic congestion and fuel consumption [4], [13]. However, despite many promising advantages, it is unlikely that automated driving systems are going to be able to deal with all conditions. At least not in the near future since driving scenarios are complex and not always predictable. Failures are anticipated when the automated driving system (ADS) is confused by conflicting information from its sensors or in situations that are not observed before. Currently, solutions for control failures are either return to human driving or stop the vehicle to solely assure safety [30]. However, applying 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 expected commercial mobility services with fleets of shared taxis [20], [47]. 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. High accessibility, uptime, optimal fleet utilization, and fleet management on a system level are fundamental for these services.

Given that each automation level defined by Society of Automotive Engineers (SAE) depends on the driving scenarios, it is crucial to view the ADS from a new perspective regarding efficient, economic and safe control; the critical distinctions are whether to have human driver in the loop in the dynamic driving tasks [53]. Currently, AVs make decisions based on the perception of the environment and predefined situations on conditional scenarios [49]. When complicated traffic rules and real situations dynamically interact, such as 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 where fleet management and optimizing the utilization of the fleet are important. 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 in air traffic control and management. The aviation industry has fully embraced automation in flight control and navigation systems since the mid-1970s [19]. 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 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 [22], [39]. Given the current development status of on-road AVs, a key question is that if a remote traffic control tower (TCT) can improve the safety, service and operation of AVs.

In practice and early trials, there are several vehicle developers exploring opportunities with remote control towers for automated road vehicles. Nissan announced that they plan to have a human remotely in a call center for their automated driving vehicles at the Consumer Electronics Show 2017 [66]. The purpose is that when cars send out an emergency signal, instead of taking over the driving, human operators in the call

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center will use the car's sensors to look around, determine the best course of action, and issue fresh instructions to the computer onboard. 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 to help the vehicle perform better next time.

Phantom Auto [71] 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, the operator in the call center can control the vehicle through a steering wheel and pedal combo. Starsky Robotics [72], a San Francisco based start-up company, 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 is 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 [64]. Uber and Toyota also have certain remote operation of AVs in an unexpected environment [65]. However, the pioneering attempts mentioned above only link with their own product development and promotion. The research on what are necessary for an AVTCT to centrally support operations, management and control of AVs, especially with regard to fleets of AVs is still scarce. Although [30] 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 integrate 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 TCTs 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?

The following 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 are discussed to get leads for Q2. This section also lists the open questions of AVTCT based on expert workshops to prove the concept and 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 2013 or later were searched since NHTSA issued their automation level in 2013 [45] and then SAE issued their standards for automation in 2014 and updated them in 2016 [53]. 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. The findings in the literature are divided into three areas. The first area is to show the three main functionalities of ADS systems. Checking this area can help identify the needs and challenges related to automated driving control. The second area is to see how TCTs are used in other transport modes. Checking this area can help learn from the knowledge of the best practices of existing TCTs. The third area is to view how human factors aspects can be related to automated driving. Checking this area can help understand why the interaction between the ADS and the human is crucial for safe and effective driving.

A. Three Functionalities in the Current ADS

The functionality of an AV is based on a complex ADS. Three of the main tasks for the ADS are perception, plan and communication and control [2], [30], [49].

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 essential 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 [3]. The perception task includes creating usable information about the vehicle and its environment [6]. It 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 in the surrounding environment [30], [69]. Sensor information relies on real circumstances and they have limitations in perceiving real time raw data [2], [36].

Perception challenges are countered by the following technological solutions: sensor systems with GPS, cameras, radar or laser range finder, and advanced automated driving algorithms [69]. 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 [52], [70]. The perception functionality prepares for realizing a better plan functionality [4], [59].

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.

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Plan in ADS is usually performed in a hierarchical manner consisting of the mission plan, route plan, behavior plan and motion plan [3].

It is crucial for AVs to have effective communication internally and externally to fulfill the planning task. Especially in mission planning since it is performed through graph search over road/path network connectivity [3]. Mission planning chooses the optimal route, avoids unsafe situations, and ready to conduct travel behavior due to mission requirements, which all leads to the next task: to execute the planned actions [35].

Connected vehicle technology can provide real-time information about the surrounding situations, improve decision efficiency and enhance safety and mobility. This also enables route and behavioral planning 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 [58].

Former studies show that V2X communication can contribute in improving road safety, availability of infotainment services and the efficiency of transportation systems [31], [32], [60]. 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 [10], [37], [69]. The Fifth Generation (5G) wireless communication systems are a promising solution enabling effective communication for connected AVs [5], [15], [18], [30], [69].

3. Control

Through perception and plan, AVs conduct mission planning to decide a sequence of actions to reach a specified goal. 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 [61]. In case of any emergencies, an emergency function will be enabled to either stop the vehicle or hand over to a human. So far, this emergency procedure is the only way in dealing with emergencies [2], [34]. Although combining with current sensor and communication technologies, the intelligence level to recognize sudden changes and react accordingly is still not reached [30].

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 [27], [63]. Reference [54] conducted a preliminary analysis and showed that, compared to conventional vehicles, AVs 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 unexpected new scenarios where 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 [46]. Second, users are skeptical to accept that AVs take over driving and control, and the universal acceptance of such a transition is not guaranteed or certain [50], [51]. 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 [46].

According to SAE, 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 automation can become publicly available at a wide scale [33], [38]. According to Nissan's R&D director Maarten Sierhuis, the truly driverless car is an unreachable goal within five years or so, humans will most likely be needed in the loop one way or another [65].

B. 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 the safe operation of aircrafts [1]. AiTC have controllers for terminals and routes. 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 AiTC system, control towers play an important role for maintaining safety and managing the traffic [55].

Traditionally, each airport is equipped with a control tower. The tower provides visual surveillance mainly through the controller's out-the-window view of the airport surface and local airspace. All surveillance and communications information is transmitted to one or more controllers in the tower. However, AiTC generates very high costs due to developing, operating and maintaining the advanced surveillance and control system. 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 [55]. 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 [21], [22].

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 vehicles. In railway control, focus is mainly on ensuring safety, regularity, reliability of service and punctuality of operations [11]. The train traffic control system aims at being able to handle more frequent traffic, higher speeds and several different companies

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operating on the infrastructure. In unmanned marine vehicles, remote control is mainly for guidance, safety and increase task efficiency [7], [36]. The need for remote control in different transport type is because vehicles failed to have correct situation awareness and performed poor human machine interfaces [12], [21], [26].

The main difference between automated on-road driving and automated (air, railway, and water) driving is that the road networks needed for automated on-road driving are more complex and intensive with different road levels and binding rules. The infrastructure in the surrounding driving environment for on-road AVs is more dynamic and unpredictable. The concerns in human factors are higher since the interactions are not only with people on board but also with people outside. Situation awareness is more complicated and harder because the traffic situation is more dynamic, undetectable and unpredictable. To answer the questions raised in the introduction of this paper, the focus in next section is on those concerns related to control of on-road AVs.

C. Human Factors in On-Road AVs

Current studies on human factors indicate that automation resolves the imprecision and variability of human task performance, but also yields new types of safety concerns [38]. Workload and situation awareness are two of the most important human factors that influence performance and safety [14]. 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 [25], [56], [67].

A fact that cannot be ignored is that ADS will occasionally fail, and a human has to resume control to for safety [24]. "Taking over control" is a primary task left for the human operator who supervises an automated system [43]. Reference [9] argued that intermediate levels of automated driving, where a human is expected to monitor, may be particularly hazardous because humans are unable to remain vigilant for prolonged periods of time. Due to the changes in the driver's role in AVs compared to manually driven vehicles, the human factors needs to be carefully considered by researchers, designers, and policy makers [14], [38], [41], [42].

Reference [56] pointed out that human factors also should be dynamically considered depending on the automation level. According to [53], in Level 2 automation, a 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" [53].

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 challenge 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 need to pay to traffic and the system, and the less capable they will be to resume control; thus, the driver may not provide suitable fallback performance of the dynamic driving task [56].

Attention has been drawn to study key performance indicators (KPI) in the response time of humans to ADS failures [40], [42], [57], [69]. For example, complacency [48], mental workload [14] and situation awareness [17], [29] 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 II and answer Q1, research has primarily focused on development of on-board systems and on the human as an on-board fallback system. Only a few studies with a focus on remote perception, plan, monitor and control for on-road AVs were found. The TCT has not been used in on-road AV control but show potential to counter challenges to reach higher levels of automation.

III. A PERSPECTIVE FOR AV TRAFFIC CONTROL

Remote control systems can act as an economic and safety backup of automated systems [30]. In remote control, one person can manage multiple AVs, take actions upon request, and take over the control after system failures [64]. Inspired by the control tower in aviation control, the AVTCT can be a potential solution to control and manage AVs in various scenarios.

It should be noted that remote control from a control tower is not the same as remote driving of the vehicle. The control tower could 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 can perform the traffic control from a holistic level to a specific individual level for fleet management, commercial services and personal travel.

A. The Role of AVTCT

An AVTCT has the potential to control vehicles when the ADS control fails. Decision-making can then be more proactive, reactive and responsive because information is processed more efficiently based on a holistic view of situations like weather data, traffic information, and movements of other vehicles. AVTCT does not only serve as a safety control center but also as a platform for handling requirements from various actors, and makes the whole transport system more efficient and intelligent. Cooperation among stakeholders and support both from the technical side and policy side can be conducted through AVTCT. Fig. 1

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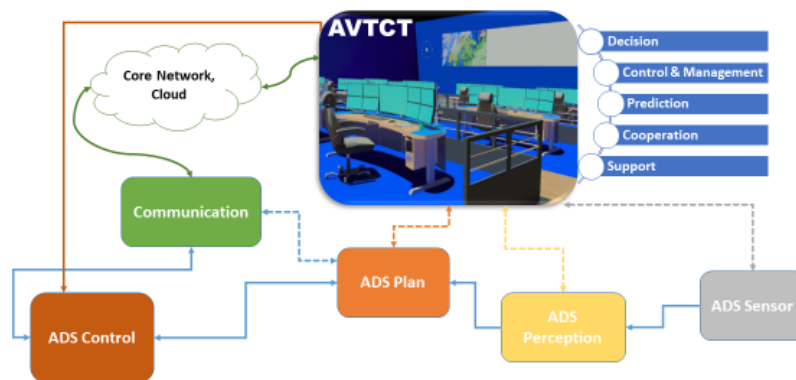
illustrates how AVTCT interacts with AVs.

Fig. 1 Potential roles of AVTCT in controlling AVs

AVTCT may provide various functions when it comes to fleet management and autonomous driving. First, similar to AiTC, one potential role of AVTCT is to assure traffic safety and increase traffic efficiency in 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 is 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 I further explains the detailed potential of AVTCT in solving the main challenges in ADS.

TABLE I
CHALLENGES IN ADS AND POTENTIALS IN AVTCT

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

B. Challenging Areas Related to 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 the literature, and there are still many considerations and challenges in configuring the conceptual framework to set up AVTCT.

In order to set up an AVTCT, many aspects need to be taken into consideration. The areas of consideration are summarized and illustrated in Fig. 2.
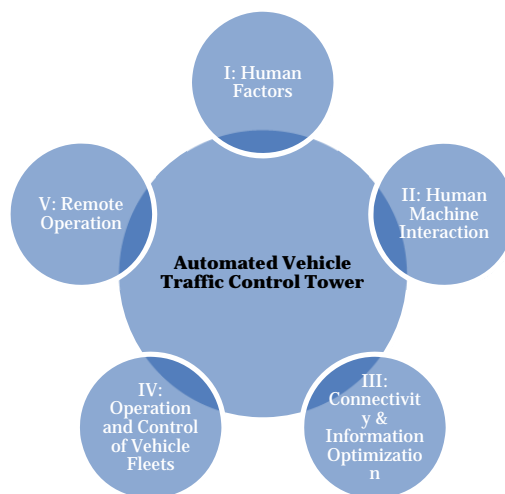

Fig. 2 Aspects to be considered in setting AVTCT

These aforementioned aspects revealed several design and operational challenges. First, it is challenging to immediately identify technical solutions and to effectively transfer the critical information between the AVTCT and the AVs. Second, it is challenging for the human controllers in the AVTCT to manage all real-time traffic information accurately and effectively. Third, it is challenging to provide relevant abstractions, visualizations and interaction modalities to support the advanced decision-making capabilities required in the AVTCT. These aspects are also reflected in the different levels of abstractions considered in the definition of features and functionalities for the future AVTCT entity. At the "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 the "Micro" abstraction level, the TCT will be required to support real-time

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control and monitoring information flows with each of the individual vehicles.

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 to take over an AV? When should the human operator in the AVTCT trust the ADS to provide 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? And 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 protocols needs to be set to bound the latency between the remote human drivers and the vehicles [30]. 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 network and optimize the data transmission under different protocols and standards [23], [28]? How should the future 5G networks be used to ensure the low latency and high bandwidth communication required for AVs [11], [62], [69]? What if there is an AV 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 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 [8], [44]?

Third, in remote operation, low latency and accuracy are crucial, for both single vehicles and fleets. Image sensing, 3D map, and vision could be delayed in the transmission, this could lead to decisions made in AVTCT that are already too late. The remote response center should be selected and/or switched based on the maximum end-to-end latency [30]. This function will be more practical as system failures are more likely to occur in denser areas with many vehicles or during road constructions. However, this is still not tested in other cases and may not applicable to AVTCT in a wider range. For remote operation, large volumes of data need to be transferred between vehicles and AVTCT. In order to provide sufficient and instantaneous information from the AV to the AVTCT, real-time streaming is needed. This leads to several questions: Which information will be transferred and at what type of resolution? How can data be filtered and compressed? What type and structure of data will be needed?

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 users, capacity and requirements on road infrastructures? 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?

2. Operational Challenges of AVTCT

To explore the challenges and uncertainties related to operating AVTCT, opinions from the AV OEMs spectrum (Volvo and Scania), the authority spectrum (Swedish Transport Administration) and the communication technology spectrum (Ericsson, Carmenta) were gathered and 42 experts on road transport, AV technology and human factors experts were gathered through three workshops within the pre-study of AVTCT project. Table II summarizes the operational uncertainties for AVTCT identified by the experts at a holistic level. In Table II, the challenges are also prioritized based on the input from the experts and categorized based on their operational uncertainty.

The ownership of AVTCT, the architecture of systems of AVTCT and respective roles in different implementation and on different levels 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 a 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 remote 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. Proof of the Concept

To address the above-mentioned challenges, prototype and demonstrations have been conducted to show how the AVTCT can be potentially designed and implemented as part of a transport system. The prototype is based on the central traffic control system developed in Drive Sweden [16] (Fig. 3) and is built up with a real traffic management control room and scaled down AVs as is shown in Fig. 4.

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TABLE II
OPERATIONAL CHALLENGES FOR AVTCT

| Operational challenges	Description	Priority level
• Ownership of AVTCT is not decided • Architecture of systems of AVTCT and respective roles in different implementation and on different level is unclear. • Contexts and conditions for AVTCT is unclear • Level of authority for AVTCT is uncertain • Levels of vehicle automation and the required control are dynamic • Efficiency requirements on AVTCT are unclear • No standardization of sensor suite • Different requirements of infrastructures in mixed traffic	• These uncertainties have the high priority as they are fundamental for the design of the AVTCT	• High
• Requirements on type and quality of data • User group, service requirements and charge for the AVTCT services • Security of vehicles and AVTCT • Level of situation awareness • Level of immersion and comprehension • Reliability of connection to the vehicle • Laws allowing remote control of multiple vehicles • Quantification of the value of AVTCT	• 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	• Medium
• Handling of technical failures • Cost and effectiveness compared to on-board drivers • Communication to passengers • Passenger trust • Digital limitations of real time traffic • Size and speed of the vehicle	• The low operational uncertainties are mainly related to the vehicle and passenger details. These uncertainties are not crucial to start the design and test of AVTCT.	• Low
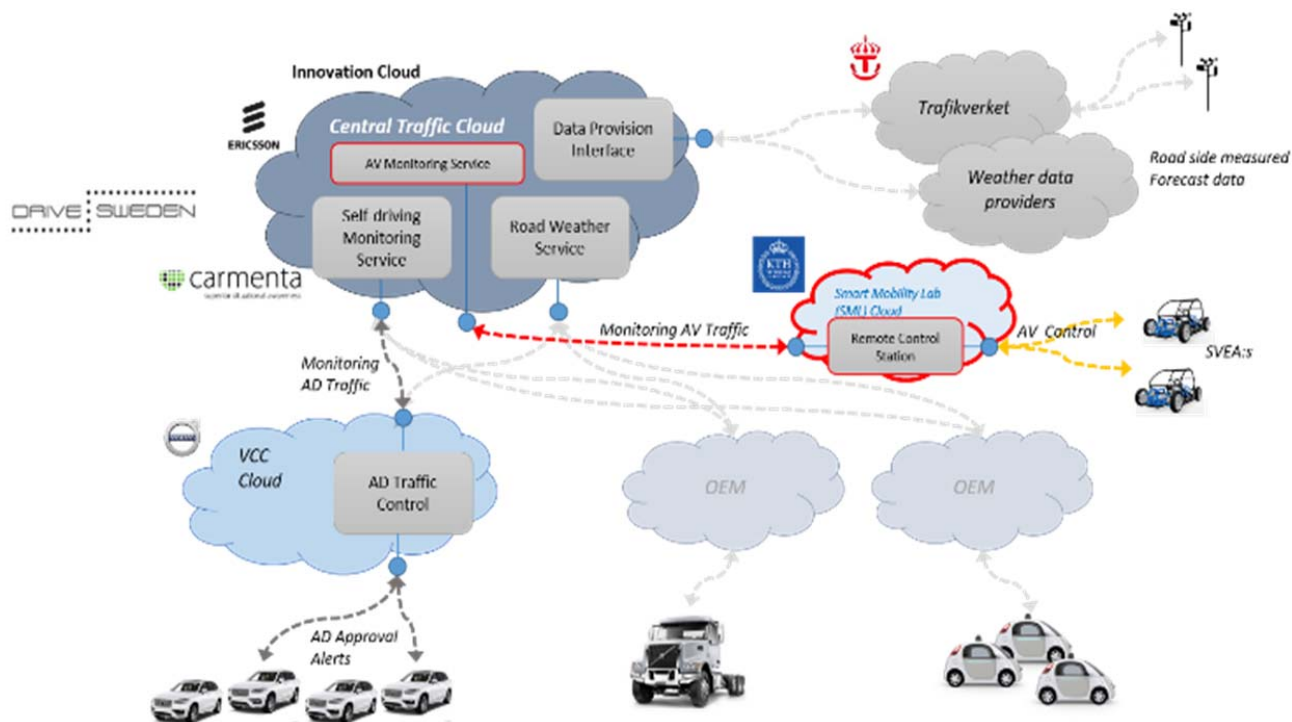
Fig. 3 A system overview of the AD Aware Central Traffic Control

In the test demonstrations, situations such as accidents, obstacles, road contractions, etc. are set. The remote control station receives a warning message when a specified distance from the incident is detected. If the vehicle is unable to resolve the situation using its automated functionality, the automation mode will be turned off and remote control will be applied. After the overtaking maneuver is done, the vehicle is set back to automation mode and continues its route (Fig. 5).

We consider the limitations of scenarios that the prototype can cover, advanced simulations and a demo system has been developed for more scenarios (Fig. 6). The simulator has been built on top of GTA V, a hyper-realistic video game. It has the ability of simulating different a) weather and time of the day, b) traffic conditions and pedestrian behavior, c) the latency in the information systems (e.g. simulating 4G or 5G settings), d) the driving behavior via steering wheel or high level controls, e) input sensors and output actuators via eye-tracking, audio and directional sound modalities. The prototype and the simulator show that the AVTCT has great potential as a safe, efficient and integrated solution for AV control.

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V. DISCUSSION

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 AVs to be able to make decisions in contradicting situations is a major hurdle on the road towards fully driverless vehicles. Second, technologies need time to develop in order to achieve the level of reliability needed to ensure safety. Third, regulations, infrastructures, and public acceptance cannot keep up at the same pace as the technology breakthroughs 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.

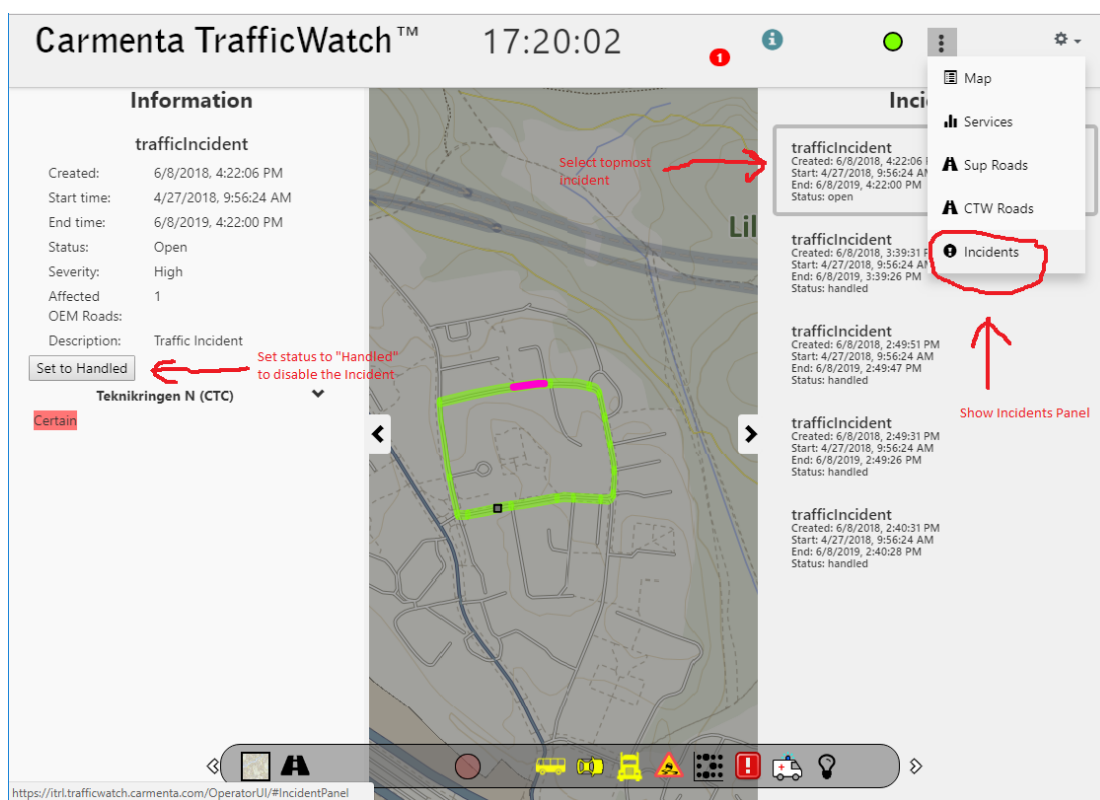Fig. 4 Prototype of remote control station and scale-down AV

Fig. 5 Example showing the interface in the remote control

This paper introduces the concept of using AVTCT as a solution to facilitate on-road AVs and to reach to the full potentials of AVs at 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 TCTs in air and sea traffic help 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.

Upon maturity, the 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 AV control failures from a perspective by introducing the TCT to remotely control and manage AVs. The development of AVs will continuously

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face new challenges, but when AVTCT reaches its potential, it may play a critical role on multiple levels for AVs control.

Fig. 6 AVTCT demonstrator: Hyper-realistic simulator

In AVTCT, one human operator can manage multiple AVs, take actions upon request, and take over the control after system failures. One potential role of AVTCT is assuring traffic safety and increasing 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 AVs in dynamic driving scenarios. Although the control tower has been widely applied in aviation, marine and railway, the contexts between automated on-road driving and automated driving in the air, on railway and in the water are different. On-road AVs need to drive in dynamic contexts that are usually composed by complex road networks, different traffic rules and changing road conditions. The interactions with the surrounding infrastructure in the driving environment are more complicated in automated on-road driving than in the other automated driving contexts. The scale that on-road AVs cover in transport is also broader and more complex than those aforementioned automated transportation modes. It is therefore novel to introduce the method of AVTCT for the operation and control of on-road AVs. 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, etc., 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 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 in the adoption of AVTCT. System effects that will be brought by AVTCT are also a focus for future work. However, while AVTCT has potential and has received much interest, including investments from the big automotive OEMs, it is still in the very early stage. Therefore, a lack of data and empirical evidence is the primary challenge to carry out more comprehensive impact analyses as well as

service and technology forecasts. Currently, available data are pending with prototype and simulations. The pilot of real AVTCT takes a long time to set up and get operational and usually combines a limited number of modes, a few parts of the entire transport system and limited geographical coverage. Thus, it is challenging to analyze and predict what kind of influence AVTCT will have in the future at the societal level and what kinds of AVTCT will be established and implemented. Therefore, it is recommended to shortly follow up the prototype as presented in this paper and update the current state and future predictions with more data, empirical evidence and knowledge.

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