Project Report
Automated Vehicle Traffic Control Tower 2

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Partners: ITRL KTH, MSL KTH, Trafikverket, Carmenta, Volvo, Ericsson, Scania, Telia

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Background

In recent years, we have continued to see automated vehicle technology rapidly evolve and enable road vehicles to perform a rich variety of autonomous tasks. This progress in vehicle automation has begun to indicate the possible benefits that automated vehicles can have on society. If we can begin to scale up deployment of automated vehicles, our transportation networks will become increasingly more safe and efficient. Moreover, through connectivity, we can become increasingly aware of the status of our transportation networks through the data flowing out from connected vehicle fleets.

In the maturity of certain autonomous functionalities, it has also become clear that automated vehicles will not and should not do certain tasks on their own. Although it is widely known that automated driving systems (ADS) are potentially safer drivers than human drivers, automated driving systems will still be restricted to operating within their operational design domain (ODD). When vehicles encounter situations outside of their ODD, they will not have a prepared response for the situation. Currently, in these situations, ADS depend on an on-board human safety driver to takeover the control of the vehicle. While this is a practical approach for handling situations outside of ADS systems’ ODD, relying on an on-board human safety driver is not an economically scalable approach to deploying automated vehicles. We initially address this problem in the preliminary study performed in the AVTCT Phase 1 project, which determined and conceptualized that a possible solution is to move the on-board human safety driver off-board. By having human operators in remote control towers, the ADS can get fallback support when required. Under this paradigm, as ADS improve and expand their ODD, a few human operators will be able to supervise an increasing number of vehicles.

In this project we extend and build on the results from the AVTCT Phase 1 preliminary study. Using the explorative findings from the pre-study, we begin to define, conceptualize, and implement control towers for automated vehicles. In particular, we disseminate definitions, architectures, required technologies, and a demonstration which are necessary for realizing the next steps of deploying the automated vehicle traffic control towers in society.

Results and objectives fulfillment

Before reporting the results of the four work packages in this project, we start by describing an important definition and conceptualization for road vehicle control towers that we have established in this project to support each of the work packages. While determining these definitions, we realized we can generalize and establish a definition for "road vehicle control towers" instead of just "automated vehicle control towers", as much of our work applies to road vehicles, regardless of their level of autonomy. In this project, we established the following definition for a road vehicle control tower:

a human-supervised entity who owns a collection of off-vehicle services which are collectively designed to monitor the real-time status and affect the operation of road vehicles, whether directly or indirectly

In our definition, we have focused on highlighting several aspects of the control tower that we have found to be important. First, it's important that the control tower is human-centered. As we found during the preliminary study, a primary reason for establishing a road vehicle control tower is for performing exception-handling with a human operator to handle scenarios that are outside of the automated driving system's ODD. Then, the definition also emphasizes that the services provided by the control tower should be off-vehicle services, however the role of the services can vary significantly depending on the type of control tower. Furthermore, we use the term "affect", as opposed to the word "control", to emphasize the fact that certain types of control towers will not have direct control over vehicles, especially when they do not own the vehicles. Instead, some control towers will have only indirect control over the vehicles or can only indirectly "affect" how the vehicles behave. For example, a confined area where a vehicle enters is able to establish the set of rules the vehicle must follow, which will indirectly affect the behavior of the vehicle.

In addition to establishing a definition for road vehicle control towers, we also conceptualized the general structure road vehicle control towers will follow in the future, which can be seen in figure 1.

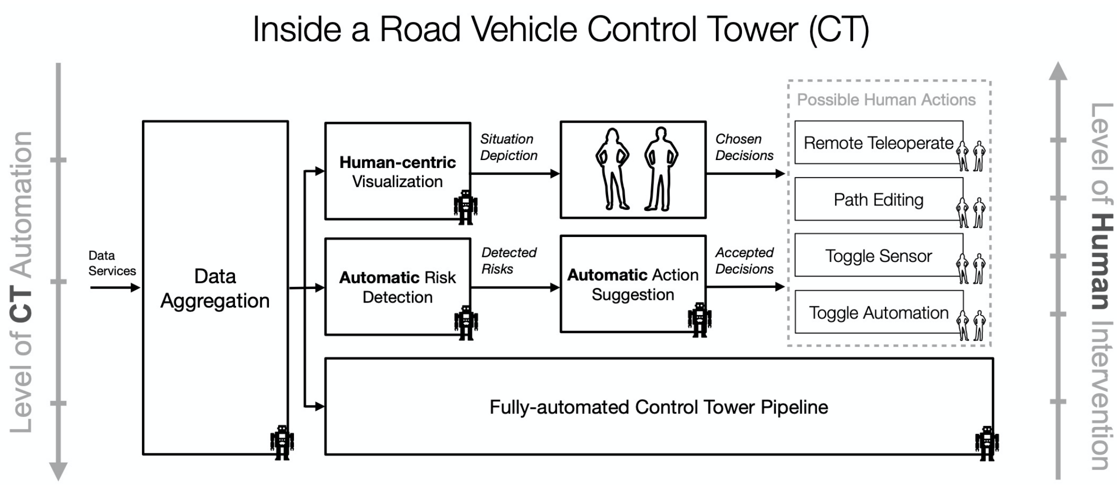


Figure 1 Level of Automation and Human Intervention in a Road Vehicle Control Tower

Two important trends that are labeled on the left and right of this figure is the increasing level of automation and the decreasing level of human intervention as we view the figure from top to bottom. We believe that this figure outlines how control towers will function in general. In the top row, after data is automatically aggregated and visualized from various sources, the decision-making is left completely up to the human operator's own initiatives. In the second row, automation helps the human by providing suggestions that the human can choose from. Finally, in the bottom row, the automation handles tasks on its own. All three of these rows will likely coexist within control towers, and the designation of tasks to each row will ultimately depend on the automation capability of the control tower itself. In other words, the control tower will also have an ODD that determines what actions should be left for the human operators to identify and handle.

With this definition and conceptualization, we can begin to report on the results of each of the work packages in this project. We start by overviewing and illustrating the ecosystem of control towers that have been determined based on extensive discussions with industry.

Control Tower Architecture

In this section the control tower architecture designed in the project will be presented. This architecture has been generated as output of several workshops organized with all the partners in the project. Moreover, individual interviews with experts have been performed as starting point in the design.

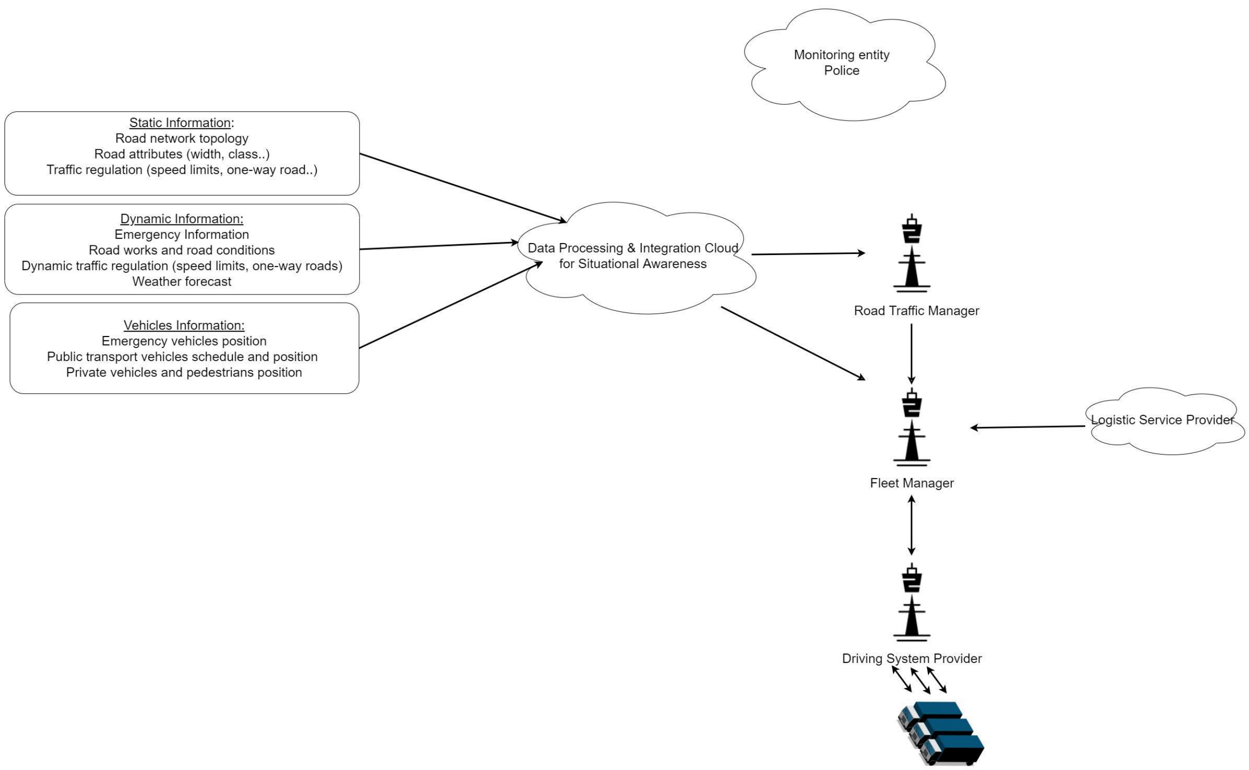


Figure 2 Control Tower Architecture

The **Driving System Provider** is the tower closest to the vehicle. It is the one that provides the vehicle with the backhand software stack for autonomous driving. For this reason, we are expecting this one to be responsible for safety during the travel and to handle emergencies by performing the manual takeover or by delegating it to another specific tower. Moreover, it will take care of collecting data from the sensors onboard and doing the first processing of them.

There will be many different Driving System Providers, some could be internal to specific OEMs. In any case, trucks automated by different Driving System Providers can be part of the same fleet. So, moving one level up in the diagram, there is the Fleet Manager Tower.

The **Fleet Manager Tower** is the one receiving the command on the fleet mission from the Logistics and the Situation Awareness. It elaborates these pieces of information, allocates resources for this mission and proposes a route for the trucks to follow.

Logistic Service Provider acts as a mission planner. It requires a certain amount of vehicles to transport goods from point A to point B in given time constraints. This information moves to the Fleet Manager that allocate a set of vehicles to accomplish this task and propose a path for the vehicle to follow using situational awareness and checking if there is the possibility of synergies with other fleets, a path adjustment might be required. Finally, the command reaches the vehicle through the Driving System Provider backhand software. Here the local planning is addressed, and safety needs to be guaranteed. The feedback from the vehicle reaches the fleet manager and feedback reaches the logistics.

Another important stakeholder that may intervene in the path decision for the vehicle is the **Road Traffic Manager**. This entity supervises the entire city area and is responsible for setting traffic rules static or dynamic. Moreover, they can define geofence and communicate relevant traffic information and warnings to the other actors.

Information and data collected from different sources are combined together to build situational awareness in the **Data Processing & Integration Cloud**. Historical data are combined with recent data and analyzed with learning algorithms that make sure the processes are constantly improving.

Interesting to differentiate between static and dynamic information. Here we call static information the one that changes with a low frequency (weeks, months, years) such as road network topology and traffic regulation. On the other hand, we call dynamic information the one that needs to be updated with a much higher frequency, such as weather, accidents, presence of emergency vehicles, public transport vehicles and dynamic traffic regulations. Some sensor data might be included as well, mainly from the city infrastructure, but also from vehicles, when possible. Precise regulatory framework needed for privacy issues and good connectivity.

A **Monitoring Entity** (for example, police) supervises the overall system to ensure the traffic rules are followed. They might intervene in case of necessity, for example deviating traffic flow in case of accident, send warning to different towers if their vehicles are approaching a dangerous area.

Input Driving System Provider	**Input Fleet Manager Tower**	**Input Logistics Service Provider**	**Input Road Traffic Manager**
- Vehicle status and performances - Sensors' data	- Mission assigned from the logistics center - Situational awareness - Information on different vehicles available	- Feedback about the vehicles position and mission status	- Situational awareness
Input Vehicle	**Output Fleet Manager Tower**	**Outputs Logistics Service Provider**	**Output Road Traffic Manager**
- Local planning - Manual takeover	- Assign vehicles to the mission	- Mission assigned to vehicles - Set constraints (e.g. route, time)	- Traffic information and warnings - Static and dynamic traffic rules - Geofence

Control tower's architecture – hub-to-hub goods transport

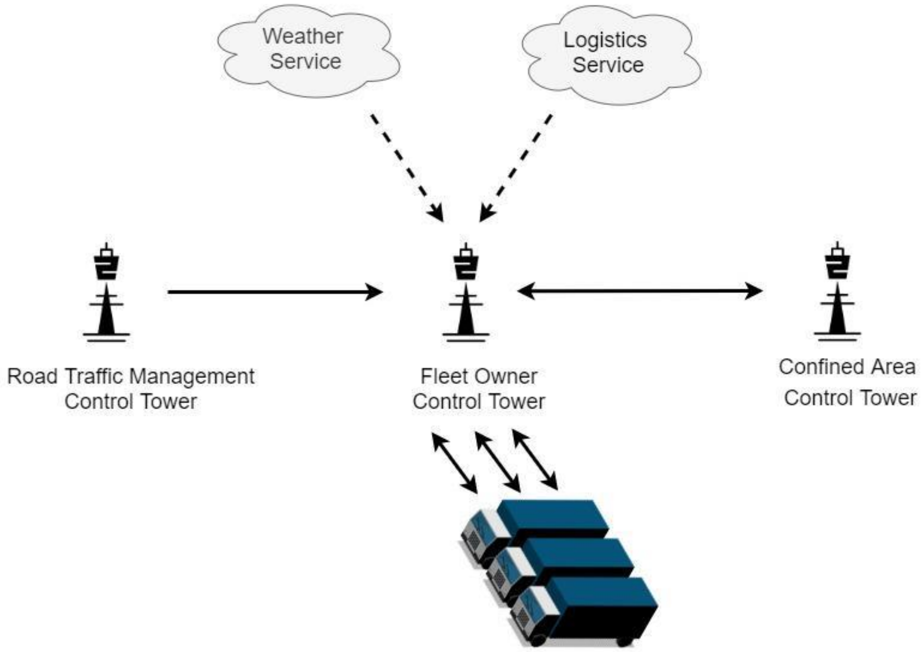


Figure 3 Hub-to-hub use case - Control Tower Architecture

In this use case, we are considering **hub-to-hub goods transport** for a fleet of vehicles. The fleet starts the journey from the first confined area where in-site operators assist the good loading on the vehicles. Then the fleet leaves the area forming a platoon, and travels through public road until reaching the second confined area. The operator from this confined area allows vehicles in and select parking spot for them, aid by software. If the parking spot is hidden or difficult to reach for the autonomous vehicles, support from the Fleet Owner Control Tower might be requested.

There are three main stakeholders involved in this scenario: fleet owner control tower, traffic management control tower and confined area control tower.

The **fleet owner control tower** is the one owning the fleet and therefore responsible for it. Automatic system or operators in this tower can take over the vehicles and make decisions on their operation. Compared to the general architecture defined in the previous section, we are considering driving system provider and fleet manager as the same entity in this use case.

The **road traffic management control tower** provides information to other actors on the traffic situation and intervenes in defining geofence and dynamic speed limits.

The **confined area control tower** is responsible for the operations of vehicle in the area. It decides who can have access to area, what is the maximum speed allowed and where each vehicle can park. Moreover, operators in-site may support the loading or unloading of goods on the vehicles.

Some other external service providers might be required, such as **Weather Information** and **Logistic Service**.

Control Tower Services and Responsibilities

Through workshops with experts, we have identified different scenarios in the hub-to-hub use case that illustrate possible interactions between actors. In these scenarios, different control towers need to collaborate in order to guarantee safety and efficiency in the operation of the vehicles. Sequence diagrams are presented to illustrate information flow between different actors involved.

Scenario 1: Vehicle approaches a confined area

When a vehicle arrives close to a confined area the driving system provider is notified about this so that it can inform the hub manager and ask permission to enter the area. Once the permission is granted, the driving system provider send the command to the vehicle to entering the hub and notify the logistic service that the vehicle has reached the hub (ready to load or unload the goods). Note that together with the permission to enter the confined are the hub manager might also provide rules or suggestions to for the vehicle (maximum speed allowed, free parking spots, warning that human operators are in the area and others).

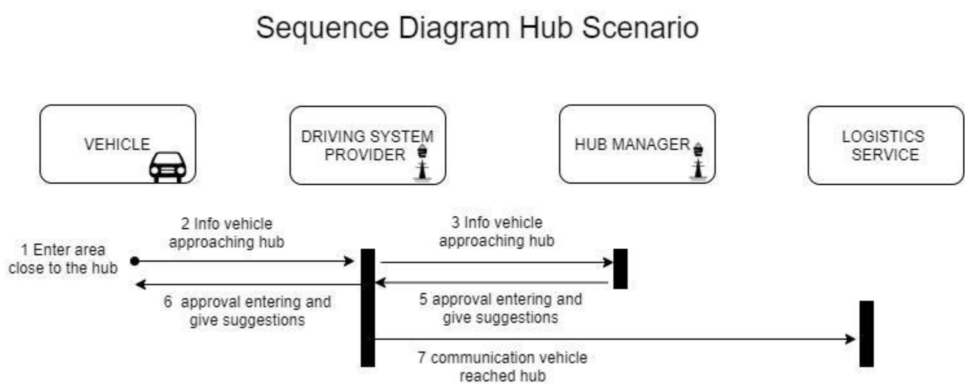


Figure 4 Sequence diagram representing a vehicle approaching a confined area (hub scenario)

Scenario 2: Vehicle approaches an area where an accident just happened

The road traffic manager notifies the driving system provider that the vehicle is approaching an area where an accident happened. The automatic system in the driving system provider tower or a human operator might do a replanning considering the set of requirements given by the logistics service. The new route is finalized and sent to the vehicle. Moreover, the logistic service is notified of the change in plan and possible delays.

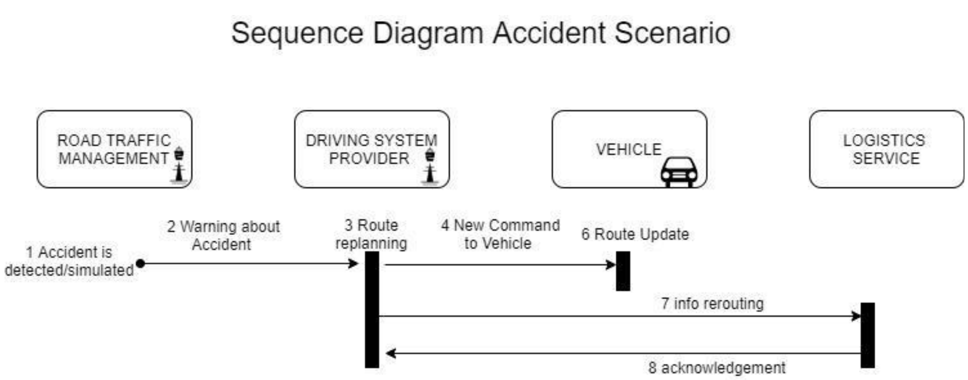


Figure 5 Sequence diagram representing the interaction between different kinds of control tower and vehicle in case of accident on the road

Scenario 3: Vehicle enters an emergency stop state and needs operator input to move forward

The vehicle enters an emergency stop state, and it requires help from the driving system provider. In this scenario, the automatic evaluation of the driving system provider is insufficient, and an operator needs to be involved in the decision. However, the automatic system can provide suggestions to the operators about possible solutions (e.g. remote control of the vehicle, call mechanic or authorities). Finally, the intervention of the operator allows the vehicle to continue its trip autonomously.

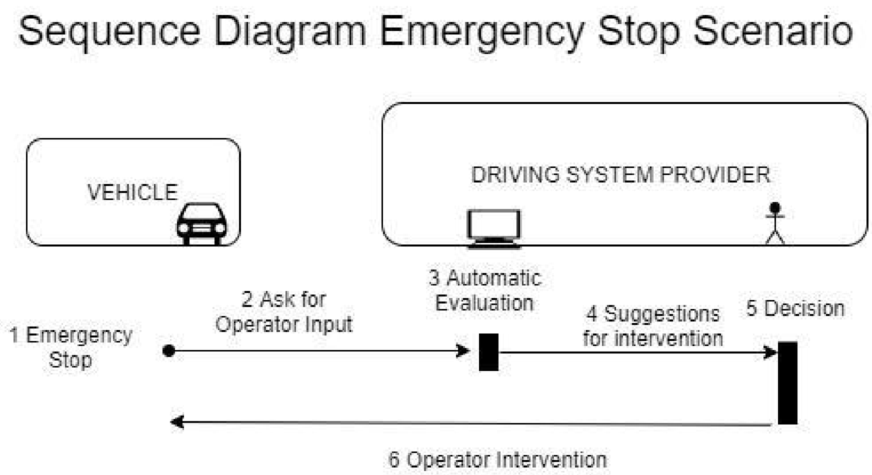


Figure 6 Sequence diagram when the autonomous vehicle enters an emergency stop status and requires intervention from the driving system provider tower

Control Tower Technology

This section summarizes the data about control tower technology collected through the workshops. The contents of the workshops were structured into two main categories. First, we discussed the existing solutions that can be used as a control tower or a part of a control tower. Then we discussed how to develop a certain control tower or different services for a control tower, what development strategies can be followed.

Existing Solutions

From the previous work package reports and control tower architecture several functional components and modules have been identified. During the workshop, it was discussed to find out if there are any service providers or solutions that can be used out of the box to expedite overall control tower development. The following figure illustrates some important functional blocks that have been taken into consideration.

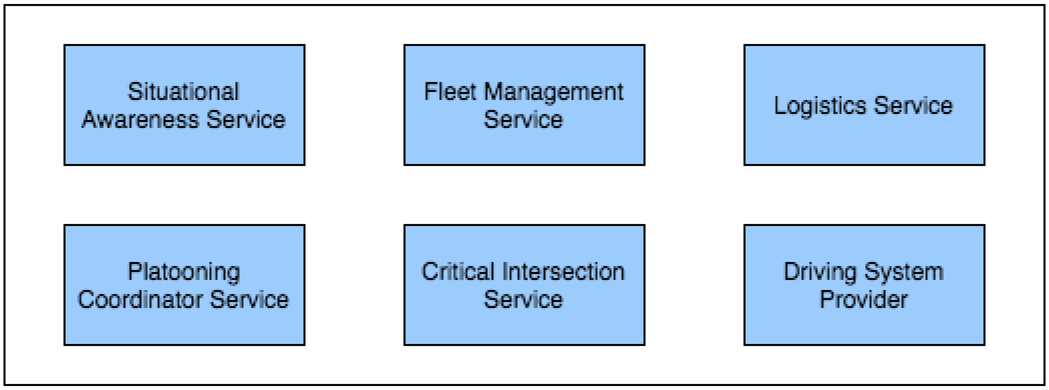


Figure 7 Functional blocks to be taken into account in the development of a Control Tower

During the discussion, it is found that there are not many ready-made solutions out of the box yet for most of the functional boxes in the above figure. The only solution available so far is Carmenta TrafficWatch for Situational Awareness. However, some participants viewed that we need more global actors to provide improved and robust functionality for critical services like Situational Awareness and Critical Intersection Management Service. There are some good service providers for Logistics and Fleet Management, but those services are mainly for manual vehicles. It is not certain that they can provide services for autonomous vehicles and at the scale the project demands.

Some of the services or components like Remote driving or Geo fencing are not listed in the above diagram. It is assumed that those kinds of services can be part of the Driving system (OEM control tower) and Situational awareness.

Quality and Security of Control Tower

While developing different control towers it is important to consider certain quality factors. So, we tried to explore this from a different functional point of view. Even though it is constrained by many different factors, some non-functional requirements have been identified that should be addressed properly in architectural design decisions.

Quality Attributes

Quality attributes also known as non-functional requirements are very important for software systems, especially for safety-critical systems. Architects of such systems must address that in their architecture design decisions and the design decisions are influenced by the driving factors of the requirements. For example, if the availability of a system is a driving factor for the business, then it must be addressed evidently in the system architecture or if you want to develop a fault-tolerant system then in the architecture there should not be any component that is prone to a single point of failure.

Following are the quality attributes that participants viewed as important for control tower development:

- Availability
- Functional Stability
- Interoperability (ability to integrate with other systems)
- Reliability

- Usability
- Security
- Performance

When it comes to the point about how to address these quality attributes in the control tower architecture, then the opinion is diverse. Some participants think it is context-dependent and constrained by the SLA (service-level agreement) and some participants think its best effort with existing resources. One of the participants viewed, we can always have better availability with some sort of redundancy. For example, for typical operations, public cloud service can be used because it brings flexibility but for certain critical operations, we can have redundant communication channels. We can create redundancy by direct radio communication either through 5G or other means of radar communications. For example, radio communication over cellular communication can be used for certain types of functionalities e.g., an emergency stop that is not dependent on infrastructure around it.

An autonomous vehicle control tower system is essentially a collection of heterogeneous systems. Some industry partners viewed it as very important to have a system architecture that is easy to integrate with other systems. So, it is important to design a system with an open mind so that it can be integrated with other systems.

Some participants also viewed that when a nonfunctional requirement like latency or availability is very critical for a system operation then it becomes a functional requirement. For example, when there is a government regulation that a human operator needs to take control of the vehicles, the latency immediately becomes a functional requirement.

The overall quality aspect of a control tower should be taken as a mission-critical system. Most of the human factor designs are nonfunctional, and these are critical. Anything related to human factor design is extremely important.

Control Tower Security

Security is the biggest challenge for control tower development. It is important to ensure that the task assigned by the control tower is validated and it's assigned to the intended entity in the network. Therefore, it is paramount to have a strongly defined and agreed security framework.

Currently, there is no agreed security framework. Some industry partners are using the latest technique like a certificate or hash-based authentication. One partner recommended the oAuth2 protocol to authenticate the services as it is a great way to build security around control tower services and it gives a lot of flexibility such as who to connect to a control tower, what levels of permission there are, and role-based access and it is also open-source, and many other open-source tools can be found around it.

Architectural Style and Communication Protocol

Architectural style and decisions depend on the requirements and the context of those requirements. During the workshop we tried to discover which architectural style can be used and suitable for different control towers. It is also necessary to define how different control towers and vehicles can communicate and exchange information.

Architecture

Microservice or Service Oriented Architecture (SOA) viewed as to be the best fit for a control tower development as currently, almost all participating companies are developing their systems around microservice-based architecture. In their opinion, a control tower can be built as a loosely coupled, distributed system with message-based communication. Some of the participating companies were informed that their core system is built as event hub-based communication.

Some partners also viewed that while designing the architecture it is also important to consider the integration of other systems. Because most of the time we need to aggregate functionality and information from many different sources and systems and it pays off when you design a system that is open to embrace other systems easily.

Communication Protocol

An autonomous vehicle control tower is an orchestration of collaboration of different data from different data sources. So, the control towers need to exchange information meaningfully and efficiently. Regarding exchanging the information, it depends on what type of information it exchanges. For example, in the case of a city or road traffic control tower when they want to exchange some event-based information, such as road work and traffic jams, etc., then AMQP (Advanced Message Queuing Protocol) would be a good choice. Nordicway project (https://www.nordicway.net/) could be one example and it becomes almost a European standards and European road authority (https://www.c-roads.eu/platform.html) has developed an IP based interface profile that provides a framework to exchange information using AMQP. There is no tight interaction between actors in the ecosystem. For example, when the road traffic authority has some information, they just published and whoever subscribed to such information they just get it. But again, when there is a requirement to separate logistics planning, perhaps it is required to have a richer protocol to exchange information.

During the discussion, it was revealed that most of the company uses message-based communication. Some of them mentioned that they are not using AMQP or MQTT out of the box, but they are using similar techniques like AMQP or MQTT.

When it comes to the point of how to communicate with vehicles from a control tower, it is viewed that we should not communicate with vehicles directly from control towers. Rather there should be a digital twin of the vehicle in the cloud and an OEM control tower should communicate with a virtual vehicle. That way it would be easy to handle some uncontrolled factors like connectivity, latency. And it will also be helpful to implement robust security between vehicle and control tower. Figure 8 illustrates a simplified communication flow of control towers and vehicles.

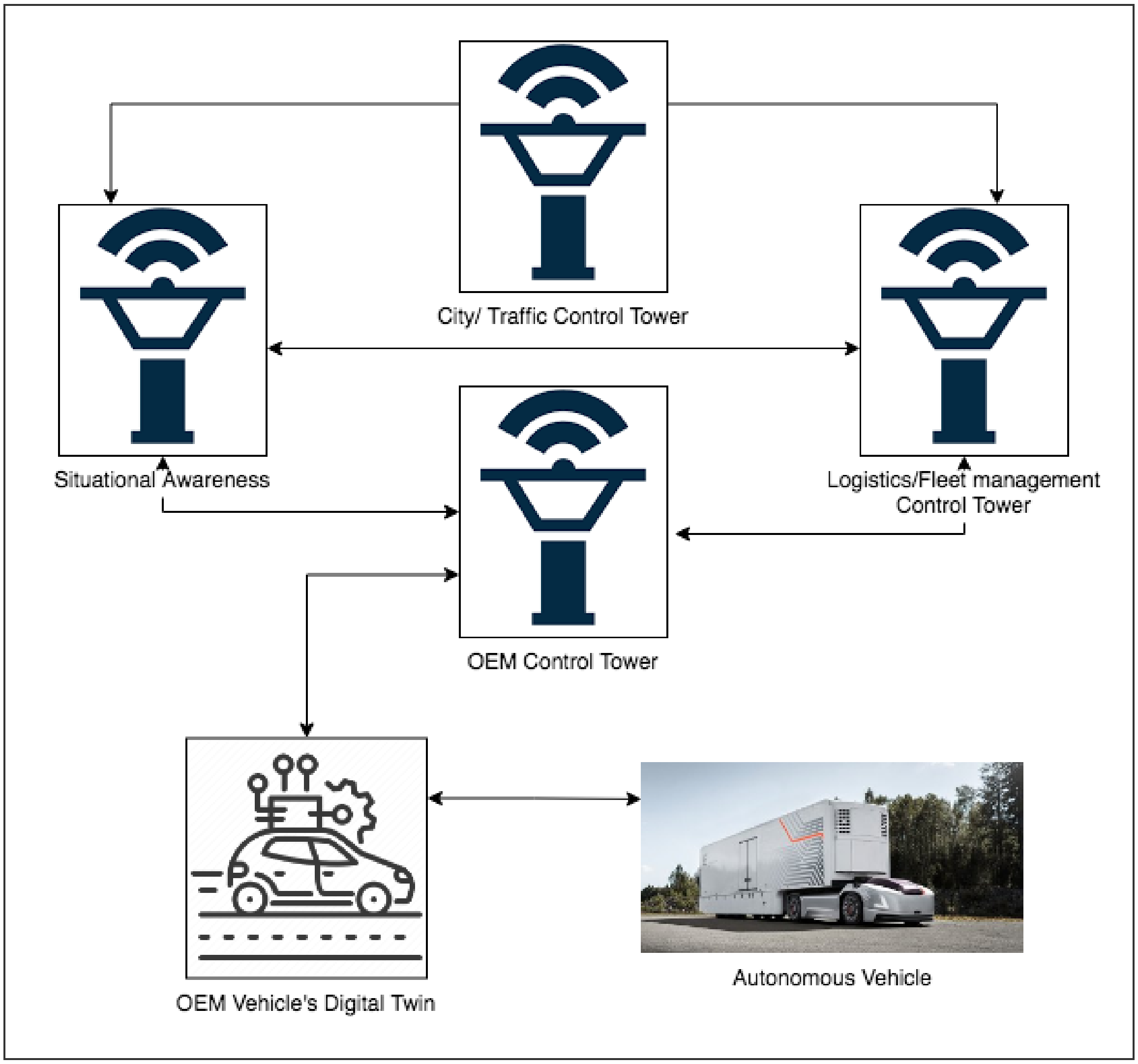


Figure 8 Simplified communication flow of different control towers and autonomous vehicles

Development Technologies and Tools

Selecting technologies and programming languages mainly depends on requirements and the team's skill set. For example, if you are building backend services then you may select any one from a range of technologies and languages like Java, C#, Python, or Go and if you are building a frontend application then you may select JavaScript or JavaScript based frontend framework like React, Angular or Vue. Most of the participating partners shared that they are doing the same and developing different microservices with different technologies and tools but at the same time they are careful not to be too diverse.

Sometimes the choice of technology and programming language is also constrained by the phase of the product development life cycle. For example, if you are building a module from the scratch then you have the freedom to choose any programming languages. However, if you need to extend or integrate any legacy system then you might not have that freedom. One participant also viewed that as a lot of functionality of control tower would be microservices and asynchronous we should select a language which is asynchronous by design.

One industry partner shared that they are developing their entire Control Tower software stack with server-side JavaScript-based technology NodeJS as it is open source and gives them a lot of flexibility to build IoT-specific services. KTH shared that in their lab they are building an experimental Platooning Control Tower using NodeJS and WebRTC which gives them flexibility and ease of use.

Serverless Technology

Serverless technology like AWS Lambda or Azure Functions is a good idea but the performance is not good for all use cases and it also depends on load and requirement on the latency. Some partners shared that they have tried both serverless and docker based services and found that people are more towards docker when they want to have predictable latency and performance. But it viewed that if the load is very little then docker may be a waste of money. It is a tradeoff between how much data we want to get processed and in how many milliseconds. For example, if we use python into the AWS lambda function then it will still take considerable time to start and goes back and forth between different services. Furthermore, if we want to have a positioning service then a docker service is more suitable as it is running all the time and there will not be any start up latency. And, if we have many vehicles, then serverless technology is not the best way to do that. To conclude, if we are not in real-time then you may use serverless technology.

Optimization Techniques, AI and Machine Learning

There are a lot of opportunities and scope to take advantage of AI and machine learning tools in control tower development. For example, for the situational awareness control tower, it is required to aggregate data from many different sources. Thus, some good data optimization techniques could boost such development. For a logistics or Fleet manager control tower AI and machine learning techniques can be used to define effective mission planning.

Almost all participating partners agreed that such AI or machine learning tools would help control tower development, but OEM partners are not willing to develop such tools. They prefer to have that service from the component provider or through an external service provider. For example, OEM is not interested in raw data from LiDAR rather they want some preprocessed data by LiDAR supplier. Most participants viewed that not many service providers are there yet to provide such services. Some partners recommended solutions offered by Carmenta for situational awareness and aggregation of data from different sources.

State-of-the-art research in this domain is very young and active. One interesting on-going discussion in the machine learning community is how to handle heterogeneous data sources, taking data from many different sources and finding something meaningful. One researcher recommended the correct-by-construction technique for optimization. Another participant viewed that we could learn from different missions we have just completed and use AI and Machine learning algorithms to optimize this.

Agile Development & CI/CD

During the workshop, we also tried to explore different software development methodologies, how to handle requirements effectively in agile development, how to set up DevOps and CI/CD. While most of the partners are currently working in an agile manner, some core artifacts of agile development like automated testing and CI/CD are hard to achieve. It seems that there is a rich set of toolchains that exist for on-board system development. But for an off-board system, like a control tower, there are not many tools yet.

DevOps, CI/CD

Most of the industry partners informed that they have a DevOps setup. One partner recommended Gitlab CI/CD. But one of the main challenges is how to perform CI/CD on a control tower where customer operation is depending on the performance of the control tower. Or maybe the customer doesn't want to update the system on the fly. It is easy to set up CI/CD for fleet management and the customer just follow us but if there is a site where the operation is depending on the performance of the tower or maybe it is necessary to fulfill some factory acceptance test or site acceptance test and where site operator needs to approve the system before production deployment then we cannot perform the CI/CD. It could also be the case that we cannot put different customers into one control tower, maybe the source code is the same, but should be a separate deployment. In some cases, it's not possible to have services like Spotify or Netflix. So, the DevOps is a bit challenging when it comes to customer operation.

Automated Testing

Testing is very complex in the control tower development domain and there is no solid framework or tool to take advantage of. But many companies are doing syntactic testing or scenarios-based testing to verify the software where they are not only covering standard cases but also corner cases. Some companies also use simulation to verify their system.

The KTH control department performed some research on formal verification of plans, whether a vehicle can complete a plan or not. Because we are a human designing a plan for the autonomous fleet without knowing if the vehicle can complete this plan as opposed to sending the plan to a human driver and human driver handle the uncertainty. It is not possible and realistic to have human operators all the time so the control tower setup is fragile, and we need some sort of formal method to verify this, and this is hard to achieve.

Deployment Infrastructure – Cloud and Edge computing

The cloud platform is predominant when it comes to the Control Tower deployment infrastructure but there is a place for Edge computing as well. For example, if we want to deploy the control tower on a mining site then maybe there is a need for local deployment and, in that case, we may have a 5G Edge node but for public road or bus service public cloud should be the primary choice. Generally, we should try to use cloud platforms as much as possible as it gives a lot of flexibility. In the situation when an Edge node is necessary maybe we do not need to deploy everything on it, only the basic functions to keep the site up and running. Of course, it is also not realistic to deploy everything on the cloud, so there is a place for hybrid setup, maybe it depends on SLA with the customer things like what up time you promise and how can you guarantee that uptime.

There is a special situation for public organizations. Trafikverket informed that they are not allowed to use any cloud platform yet, but they are following the development around it. There is a European project called GAIA-X, a common European cloud solution for the public sector, an alternative to commercial cloud solutions.

Prototype & Demonstration

In this project, we made a significant effort into continuously prototyping and demonstrating key concepts from the other three work packages. By prototyping and demonstrating concepts as they were developed in the other three work packages, we were able to further enrich their development by learning about potential issues a control tower implementation can run into through implementing an experimental ecosystem of control towers. The scenario we used to develop our ecosystem is presented in figure 9.

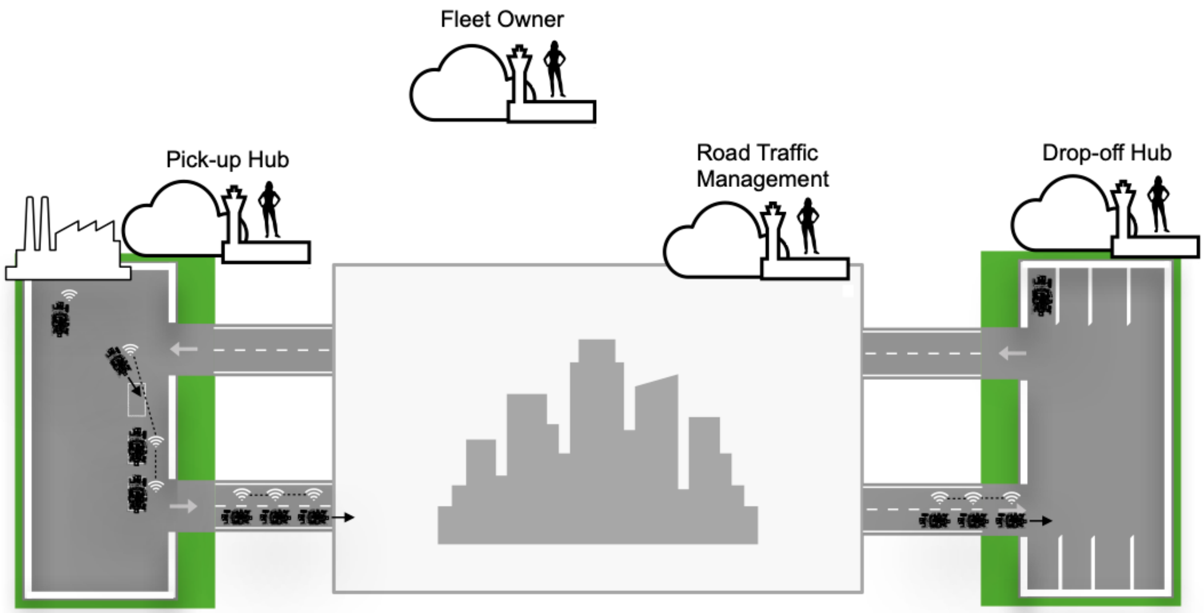


Figure 9 Representation of the scenario used to develop the experimental ecosystem of control towers

As can be seen in figure 9, our demo scenario centers around a goods transport example. In the scenario, a fleet of vehicles, who are supervised by a fleet owner control tower, start out in a pick-up hub. In the pick-up hub, the vehicles need to follow the rules and protocols set out by the pick-up hub's supervising control tower. Then, once the vehicles have been loaded with their goods, they form a platoon and dispatch onto the public road network. Once on the public road network, they need to follow the rules of the road traffic management control tower. Within the public road network, the fleet of vehicles might encounter various incidents that are resolved by the fleet owner control tower, which utilizes several services and control approaches on different levels of human intervention. Then, when the fleet of vehicles arrive to the drop-off hub, they once again need to follow the rules set out by the drop-off hub's supervising control tower to dissolve the platoon and deliver the goods to the correct locations.

One challenge with the context we laid out for our prototyping and demonstration for this project is the scale of the context. Since we conducted our implementation and development in a lab environment, it's infeasible to set up a public road network to the scale that is interesting for understanding how control towers interact with each other and handle sparse incidents throughout the road network. To handle this, we designed a realistic simulator using Virtual Test Drive (VTD) from MSC software, to emulate an important road network for transport in Stockholm. However, we also found it important to evaluate the concepts on real hardware, where we can test with realistic connectivity conditions and with real robotic systems that more closely represent the behavior of automated vehicles. Thus, we implemented a hybrid platform that uses both real hardware and simulation.

In the two confined areas, we utilize the Small Vehicles for Autonomy (SVEA) platform at the Smart Mobility Lab. We set up scaled-down confined areas where we can project different setups for the fleet of SVEAs to navigate around. In our confined areas, we also had access to the 5G network at KTH, allowing us to test concepts such as remote driving with 5G. Then, when the fleet of SVEAs leave the confined areas, our simulation in VTD will spawn a fleet of vehicles corresponding to the fleet of SVEAs at the exit of the confined area in the simulated Stockholm environment. When the fleet of simulated vehicles enter a confined area in the simulated environment, then the fleet of SVEAs become active and act as the fleet of vehicles in the scenario. This setup allows us the prototype and demonstrate on both realistic hardware conditions and on large-scale environments.

In our control towers, we also demonstrated two types of interfaces for the human operators. The first type of interface we demonstrate in the control tower is a situational awareness interface that utilizes TrafficWatch ™ from Carmenta. The situational awareness interface provides a tool for the human operator to use to understand the overall situation of the managed vehicle fleet and the transport network the fleet operates within. The second type of interface we demonstrate is an augmented reality interface, where we provide video streams to the human operator through infrastructure cameras or on-board cameras and augment additional features onto the stream to enhance the capability of the human operator.

In the following sections, we describe the different components of our demonstration platform in more detail.

SVEA Platform

The Small-Vehicles-for-Autonomy (SVEA) platform is a scaled down automated vehicle that has the capability to run on-board control and machine-learning algorithms using real robotic sensors that are analogous to the ones used by full sized automated vehicles. The SVEA platform was chosen to represent the connected vehicles in our demonstration scenarios in the confined areas due to their small size and computational capabilities. The SVEA platform is an in-house developed system that was originally designed and built for the preceding AVTCT study. Since the previous AVTCT study, the SVEA platform has matured and been replicated to form a vehicle fleet that we could use to evaluate the new control tower research conducted in this project.

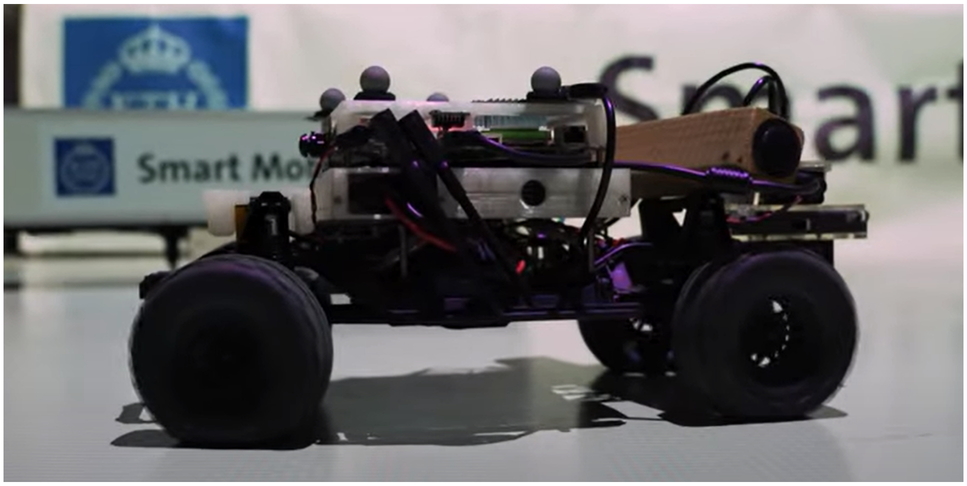


Figure 10 Small-Vehicles-for-Autonomy (SVEA) platform

Stockholm Transport Simulation

As mentioned above, we set up a simulation of an important transport route in Stockholm for our demonstration. By using VTD, we are able to simulate a rich variety of events along the transport route. In VTD, we can simulate weather events that affect road conditions, road blocks that vehicles cannot physically pass through, pedestrians, other vehicles, and more. Since one of the primary purposes of a control tower is to respond to unplanned events, using VTD for our simulation was important to allow us to evaluate how the control tower should respond to different events that might happen throughout it's transport route. This would have been challenging to do in a controlled manner using real vehicles like the SVEA platform or a full-sized vehicle.

TrafficWatch ™

Carmenta TrafficWatchTM is a cloud-based, customizable command and control solution that supervises, guides and controls the operation of connected, automated and autonomous vehicles. The core function is to support these operations by collecting and analyzing data about the surrounding environment and traffic situation to detect upcoming risks and distribute warnings, guidance and instructions to connected systems and vehicles.

Carmenta ControlTower TM extends Carmenta TrafficWatch™ with automated tools for decision-making in the management and operation of vehicle fleets and is designed to collaborate in real-time with other parts of a fleet management solution, such as planning and logistics systems.

An instance of Carmenta ControlTower was setup by Carmenta to provide a Situational Awareness overview for the chosen study area; an important road network for transport in Stockholm. Carmenta ControlTower was then extensively used for prototyping and demonstrations as the “Fleet Owner Control Tower” as depicted in the figure 8. Its main role in the trials was to receive traffic data from the “Road Traffic Management Control Tower” for maintaining a traffic situation picture for the area chosen in the “goods transport example”. Different scenarios were then tested where Carmenta ControlTower detected different Incidents causing hazardous situations on the public part of the transport route in the hub-to-hub use case.

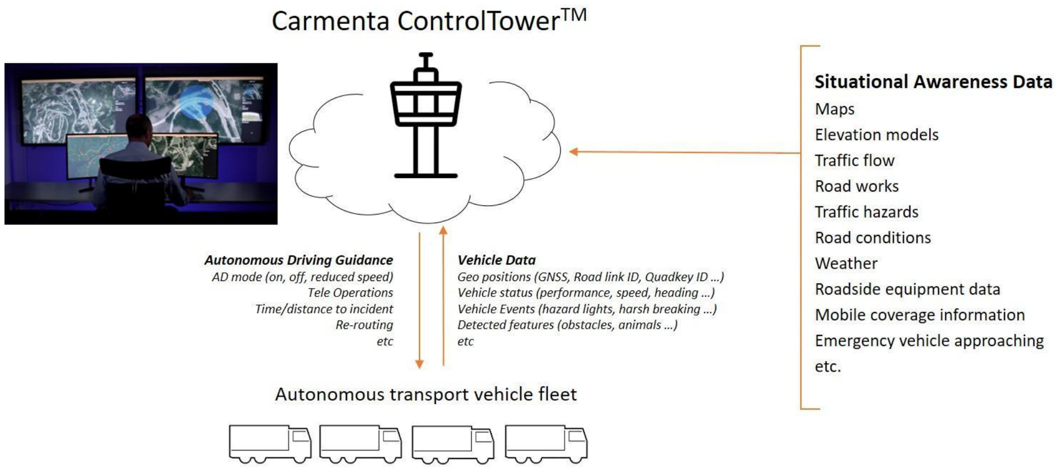


Figure 11 Schematic view of Carmenta ControlTower as a provider of Situational Awareness overview in automated driving systems (ADS)

The web-based Operator UI that comes with Carmenta TrafficWatch was adapted as the "Situational Awareness Interface" in the project for demonstrating how a human operator can get an overview of the managed vehicle fleet as well as the transport network it operates within. Tested was also different methods to dispatch guidance and/or warning messages to connected control towers and/or vehicles based on the principles discussed following the "Inside a Road Vehicle Control Tower" Figure, and summarized as:

- The decision-making is left completely up to the human operator thus using the ControlTower for fleet status overview and general situational awareness and to be notified through the UI when Incidents happen.
- A semi-automatic ControlTower that helps the human operator by providing suggestions that the human can choose from, such as setting a lower speed (from the Operator UI) to vehicles driving on route segments affected by Incidents.
- A fully automated ControlTower that handles tasks on its own such as geofencing functions that detects and automatically dispatch control message when a vehicle is crossing a virtual border e.g. an electro mobility zone.

Figure 11 shows a screenshot from one of the demonstrations where the Operator UI map is centered on a part of the supervised public transport route (green route segments = OK) where a traffic incident has occurred (red segment) that has forced one of the simulated vehicles (white and blue marker) to go into emergency stop state (speed = 0 km/h) before entering a hazardous route section (yellow segment). The human operator has in this case to decide what action to take.

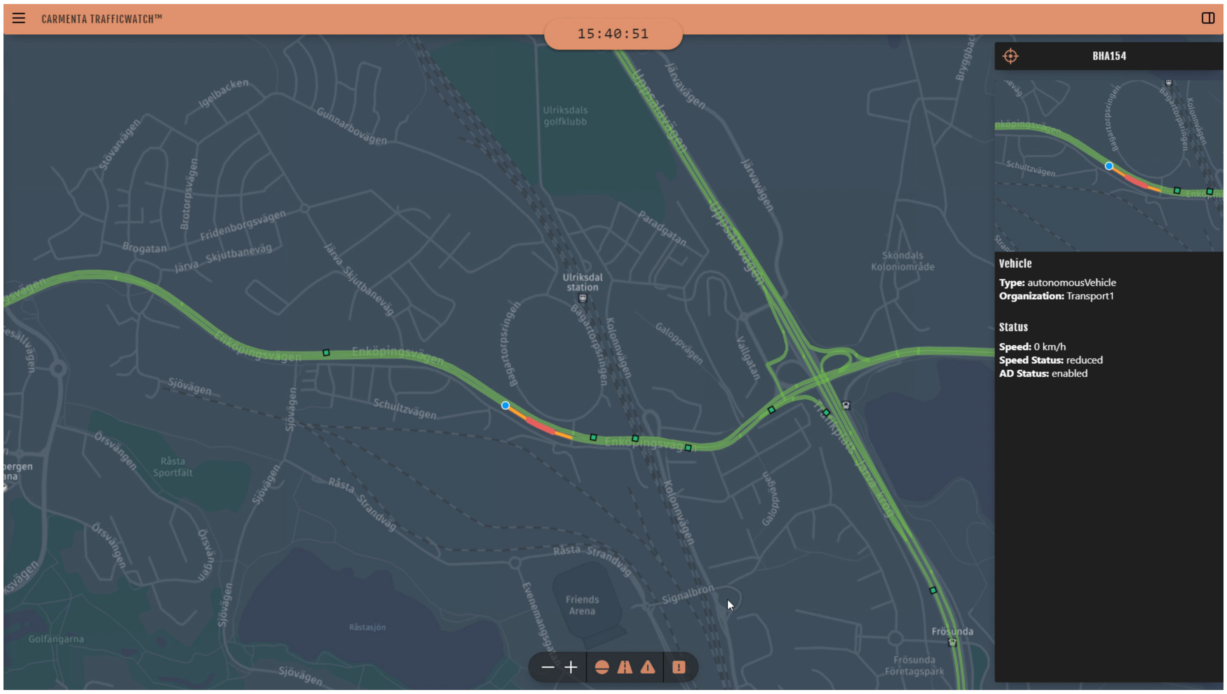


Figure 12 Screenshot from Carmenta ControlTower Operator UI showing a part of the supervised transport route with an ongoing traffic incident causing one of the simulated vehicles to make a safe stop

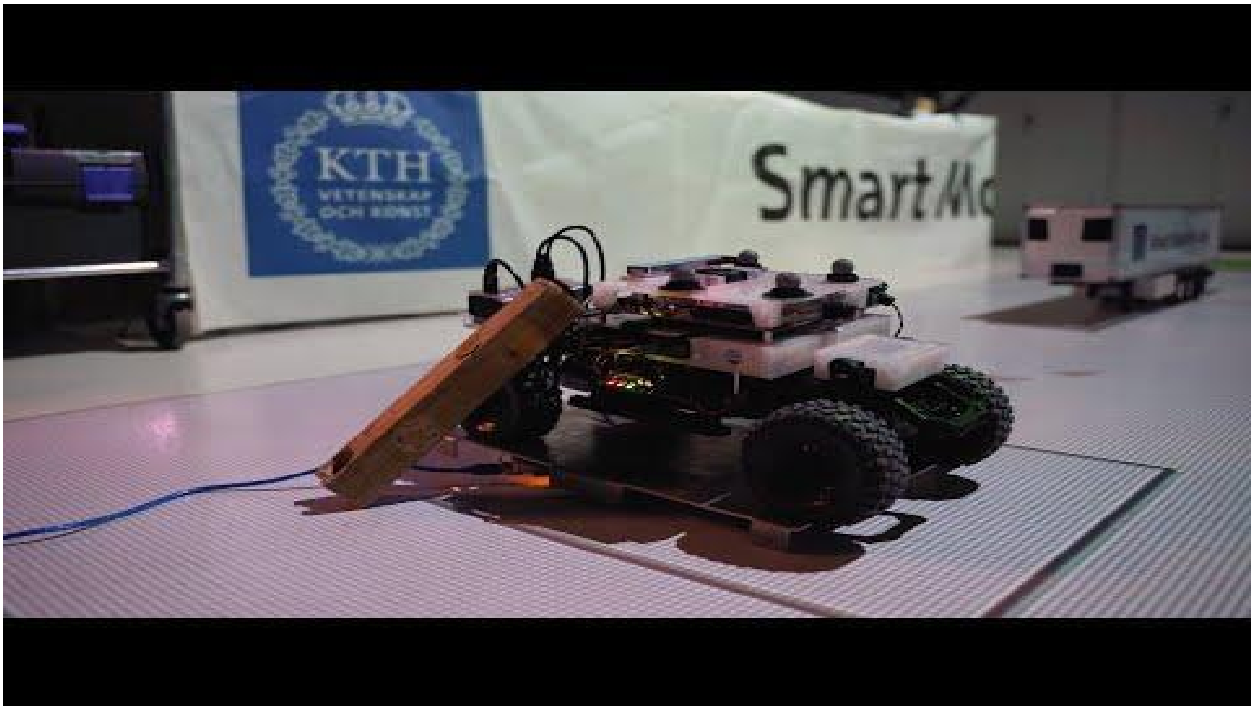
The project also prototyped and tested the collaboration and "hand-over" messaging between the "Fleet Owner Control Tower" and the "Confined Area Control Tower" where simulated trucks supervised by the fleet owner control tower, start out in a pick-up hub, drives on a public road network and ends up in a drop-off hub. When driving inside the hubs the vehicles need to follow the rules and protocols set out by the hub's supervising control towers.

Carmenta valued very much to be an active project partner and contribute to the continuous prototyping and demonstrating of key concepts set forth by the project effort to further develop the ecosystem of control towers. An instance of Carmenta ControlTower was setup to successfully support the three different scenarios in the hub-to-hub use case that illustrate possible interactions between actors. In these scenarios, different control towers need to collaborate in order to guarantee safety and efficiency in the operation of the vehicles.

Dissemination

A film of the full demonstration on the developed platform can be seen here:

Automated Vehicles Traffic Control Tower 2 – Exploring the ecosystem of Control Towers



(https://youtu.be/-ocMhlnf3PQ)

The results of the project have been presented at:

- ITRL Webinar,
- Drive Sweden Forum 2021,
- TRB Automated Road Transportation Symposium (ARTS21) - Breakout session Remote Support for Automated Vehicle Operations.

Future research

This project have shown the high potential of Control Tower (CT) as it will play an important role in the development of an automated transport system. Several types of control towers will be needed, depending on the objectives of different actors (e.g. vehicle manufacturers, vehicle owners, road maintenance, traffic management) that can work together in an ecosystem. A first simple ecosystem of towers has been identified to support operation of a fleet of autonomous vehicle in a hub-to-hub scenario.

The aim will be to expand the testbed designed in the previous projects to further investigate the concept on CT. Focus will be on understanding the role and tasks of human operators when supervising and controlling multiple vehicles while defining standards and API for communication between different towers.

Future developments on the testbed include:

- use testbed to investigate how to combine different information sources,
- use realistic simulation environment to test how a CT operator can supervise/control multiple vehicles,

- use realistic simulation environment to test how a CT operator can manage multiple fleets (from different FOCT) approaching the same confined area.