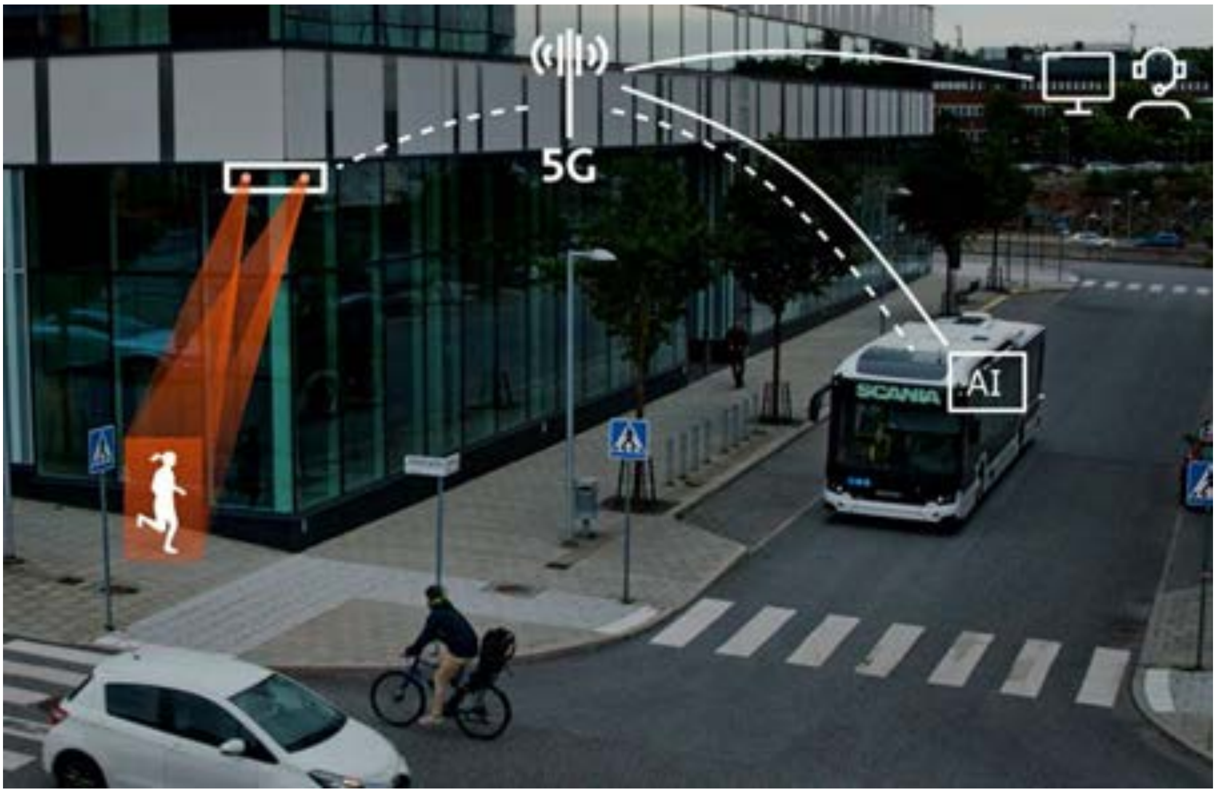
Future 5G Ride

- Final Report



Författare: Ericsson AB, Telia AB, Intel Sweden AB, Region Stockholm, KTH ITRL, Scania CV AB, Viscando AB, Vy AB, Kista Science City AB and Applied Autonomy

Datum: 20250218

FFI Effektiva och uppkopplade transportsystem

FFI Fordonsstrategisk Forskning och Innovation

Table of Content

1. Summary

The **Future 5G Ride Project** is an innovative initiative based in Kista Science City, aimed at accelerating the development and scaling of autonomous transport solutions to create a safer, more efficient, and sustainable transport system in Sweden. Beyond technology, the project explores the implications of autonomous systems on workforce roles and equality, aiming to lower barriers for scaling solutions and ensuring societal alignment. Collaboration between industries and public sectors is central to its success.

The project has over a time period of 39 months with a consortium engaging a total of 12 actors from both the public sector, industry and academia structured a collaboration around two primary objectives:

1. **Fleet Supervision and Passenger Communication**: Developing capabilities for centralized traffic towers to monitor autonomous fleets and communicate with passengers.

2. **Enhanced Situational Awareness**: Improving autonomous systems ability to handle complex traffic scenarios by integrating external sensor data with onboard systems.

Fleet supervision and passenger communication have been explored with the perspective of both passengers and drivers through reference groups experiencing the use of solutions developed by the project as well as analyzing the situation of today's drivers. AI and 5G have been used to detect and communicate abnormal behavior and through automatic action or manual aid from a traffic tower the situation is handled. The possibility with 5G of securing a redundant high-quality connection at all times is crucial to be able to deliver a safe ride. This increases the conditions for equal travel and influences the experience of a safe journey.

The project has explored situational awareness through the development of a traffic tower handling data from both the vehicle as well as fixed infrastructure sensors and thus showcased the possibility of a safer and more efficient transport system.

With the ability to look around the corner with infrastructure sensors collisions can be avoided. Furthermore, with a better overview less speed changes of vehicles can be achieved which is both favorable for the environment as well as enabling a more effective transport system.

To conclude, the Future 5G Ride Project highlights how 5G and AI technologies can address critical challenges, including safety, efficiency, and scalability, in autonomous transport. By integrating cutting-edge technology with societal considerations, the project paves the way for a transformative shift toward sustainable, autonomous mobility solutions. It serves as a model for cross-sector collaboration and innovation, advancing the deployment of autonomous systems in Sweden and beyond.

2. Swedish Summary

Future 5G Ride-projektet är ett innovativt initiativ baserat i Kista Science City, med syfte att påskynda utvecklingen och skalningen av autonoma transportlösningar för att skapa ett säkrare, mer effektivt och hållbart transportsystem i Sverige. Utöver teknologiska framsteg undersöker projektet de autonoma systemens inverkan på arbetsroller och jämlikhet, med målet att sänka barriärerna för att skala lösningar och säkerställa samhällelig anpassning. Samarbete mellan industrin och den offentliga sektorn är avgörande för projektets framgång.

Projektet, som sträcker sig över en tidsperiod på **39 månader**, har engagerat ett konsortium bestående av totalt **12 aktörer** från offentlig sektor, industri och akademi. Samarbetet har strukturerats kring två huvudsakliga mål:

1. **Flottövervakning och passagerarkommunikation**: Utveckla kapacitet för centraliserade trafikledartorn för att övervaka autonoma flottor och kommunicera med passagerare.
2. **Förbättrad situationsmedvetenhet**: Förbättra autonoma systems förmåga att hantera komplexa trafiksituationer genom att integrera extern sensordata med fordonens interna system.

Flottövervakning och passagerarkommunikation har utforskats ur både passagerarnas och förarnas perspektiv genom referensgrupper som har testat projektets utvecklade lösningar och analyserat dagens situation för förare. **AI och 5G** har använts för att upptäcka och kommunicera avvikande beteenden, och situationer hanteras genom automatiska åtgärder eller manuell hjälp från ett trafikledartorn. Möjligheten med 5G att säkra en redundant högkvalitativ anslutning är avgörande för att kunna leverera en säker resa. Detta förbättrar förutsättningarna för jämlika resor och påverkar upplevelsen av trygghet under resan.

Projektet har också utforskat situationsmedvetenhet genom utvecklingen av ett trafikledartorn som hanterar data från både fordon och fasta infrastruktursensorer. Det har därmed visat på möjligheten att skapa ett säkrare och mer effektivt transportsystem.

Genom att "se runt hörn" med infrastruktursensorer kan kollisioner undvikas. Dessutom kan färre hastighetsändringar uppnås, vilket är gynnsamt både för miljön och för att möjliggöra ett effektivare transportsystem.

Sammanfattningsvis belyser **Future 5G Ride-projektet** hur 5G och AI-teknologier kan adressera kritiska utmaningar, inklusive säkerhet, effektivitet och skalbarhet inom autonom transport. Genom att integrera banbrytande teknik med samhälleliga överväganden banar projektet väg för en transformativ övergång till hållbara, autonoma mobilitetslösningar. Det fungerar som en modell för tvärsektoriellt samarbete och innovation, vilket driver fram användningen av autonoma system i Sverige och internationellt.

3. Background

The 5G Ride project [8,9], a prior project to the Future 5G Ride, aimed to be a pioneering initiative by developing and testing technologies supporting 5G-connected autonomous electric vehicles. The Future 5G Ride project should demonstrate the potential of autonomous vehicles by adding possibilities for remote assistance and demonstrating external and internal sensors for extended security and safety. The project united a diverse consortium of partners, working together to challenge and innovate within autonomous driving and sustainable transport.

The behaviour and demands in people's daily life, in combination with the transport possibilities provided has taken us to where we are today. The development of autonomous technologies must take that into account to be accepted. Using the new possibilities in a good way, gives the possibility to create a shift to a more sustainable society.

Autonomous development in the world

During the time of the project the development of autonomous vehicles have continued, different vehicles are running in live environments in locations around the world. In transportation of goods known actors like Scania are running vehicles in mines. Fairly new actors like Einride are more into running in logistic centres and local transportation.

In transportation of people, actors like Karsan run regular sized (8-12 meter long) public transport buses in different locations, e.g. together with Applied Autonomy in Stavanger (Norway). Actors like Waymo (USA) and Baidu (China) run commercial taxis with autonomous vehicles. Waymo reports more than 150 000 commercial taxi trips every week (October 2024) with the service running in parts of four cities.

4. Project set up

4.1 Purpose

The Future 5G Ride project wants to speed up development of and scaling autonomous solutions creating a safer, more efficient and sustainable transport system on our roads in Sweden. Not only by developing the technology, but also looking at the implications of an autonomous system, the project aims to contribute to lowering the threshold of scaling existing solutions. Furthermore, the project visualizes the importance of collaboration over different industries and the public sector enabling a more capable traffic tower with a result of safer and more efficient transport. The project wants to point out how the transition to autonomous solutions can affect the tasks and workforce in public transport, with focus on equality.

4.2 Objectives

The project has investigated autonomous transportation systems in several dimensions. The activities in the project were grouped into two main goals:

1) Enhanced possibilities for supervision of a fleet of autonomous vehicles and communication with passengers, from a manned traffic tower.

2) Improved situational awareness for the autonomous vehicle to better handle complex traffic situations, using sensors in the road infrastructure, to complement the vehicle internal sensors.

In this way custom vehicle concepts as well as the human in the changed system are explored. Furthermore, vehicle and mobility services, regulations and infrastructure are put into context aligning with the strategic goals of FFI.

4.3 Project period

Project period: 39 months, december 2021 until february 2025

Total project budget: 31 276 200 sek of which public funds 14 952 620 sek

4.4 Partners

The composition of actors in the Future 5G ride project changed over time, towards the end of the project 10 actors were involved, over time the project has engaged 12 actors.

The project was initiated by Kista Science City together with Keolis AB, Ericsson AB, Telia AB, Intel Sweden AB, T-Engineering AB, Region Stockholm (Trafikförvaltningen), KTH ITRL, Scania CV AB, Viscando AB. Keolis AB and T-Engineering was in a later phase replaced by Vy AB and Applied Autonomy.

Fig. 1. All actors that have been involved in Future 5G Ride.

5. Method and activities

To explore the objectives of the project, use cases have been defined and further explored in the project's digital and physical testbeds. The user experience of both drivers and passengers have been analyzed through interviews. Passengers have also experienced and evaluated the autonomous solution in the testbed in Kista. Scenarios challenging communication with passengers where quality on demand has been activated have been tested and showcased. Automated actions generated by the AI as well as actions from the traffic tower to handle the situation have been explored and showcased.

To further analyze the situational awareness of the vehicle, connectivity and collaboration with infrastructure sensors have been carried out in the testbed in Södertälje. Furthermore, demonstrations have been completed in Kista in the urban environment showcasing and evaluating progress in the project.

5.1 User Acceptance of Automated Vehicle in public Transport

In the Future 5G Ride project, the user experience was collected by interviews with drivers and passengers of public transport. The aim was to find out how autonomous driving of vehicles affects the experience as a passenger, and what impact and possibilities for staff in different roles is thought to have.

With the support of sensors, the project showed how unforeseen events on board such as a sudden illness, assault or a forgotten bag can be identified. Alarms are automatically sent to the traffic tower where the operator can take on the right action. This increases the conditions for equal travel and the project analysed, by researchers, what influences the experience of a safe journey.

For passengers it seems that the experience of safe and secure traveling can be maintained. The smoothness of driving gives a positive effect and the secure feeling can be maintained with some technical support and possibility to have contact with the traffic tower. A vehicle without physical contact with staff isn’t anything new in public transport since that’s the situation in the subway and in many trains and trams.

With autonomous vehicles operated from a traffic tower, the traditional role of the vehicle driver will change. The project analysed, by researchers, how to work to ensure that this changing of the professional role contributes to an equal workplace.

For staff there will be some changes, especially for drivers. These will have a more controlled environment to work in, for temperature reasons as well as safety. Being a driver on distance as support will also give the possibility to be relieved for breaks as for coffee or toilet visits. For drivers there will be an efficiency effect, since it is a problem to recruit new drivers today the working conditions will give the position a better situation.

The full results from these works can be found in separate reports [10].

5.2 Safeguarding passengers using AI and 5G in autonomous buses

Autonomous shared mobility has the capability of changing the way we think about transport in the future. Optimised utilisation of the vehicle fleets and providing better and cost-efficient services for more people, contributes to more sustainable transport solutions. To make autonomous vehicles cost-effective for transport operators, the safety driver must be removed from the vehicle. New services and collaborations will be necessary when automating the transport process when the driver is no longer onboard. Remote monitoring and assistance of the operation over a stable high-capacity mobile network will be required.

The drivers today do several things in addition to the driving task, like communicating with and looking after the passengers, ticketing, checking the vehicle before and after operation or calling for assistance if people are acting violent in the vehicle. In addition to automating the driving task, the activities above also need to be considered for automation or change.

Use Cases

Several use cases that can support some of the situations that the driver handles today, have been identified and prioritised for this project. A number of possible use cases are listed in Fig. 2, both for situations inside the autonomous vehicle and relating to its connection to a remote operator in the traffic tower (upper right) through the 5G network.

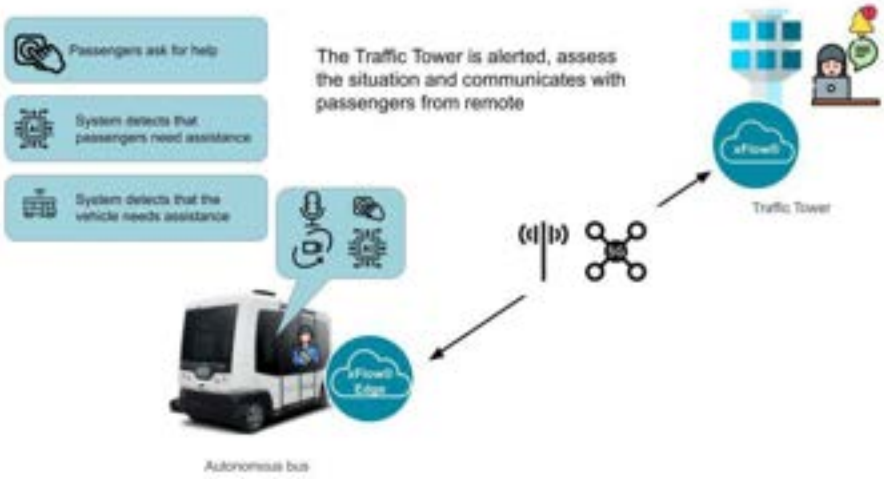


Fig. 2. Use case diagram for a passenger assistance system in autonomous operation.

Use Case: Passengers ask for help.
A passenger needs help or has questions and presses a button on the bus to request assistance. Then an alarm goes off in the traffic tower and an audio/video conversation is established between them so that the remote operator can assist the passenger. Here, it can be anything from the passenger being scared or having questions about the bus stops.

Use Case: System detects that the passengers need assistance.
A passenger is alone in the bus, and for example falls over. An AI model will, based on video information, be able to detect that the passenger has fallen, and the system will generate an alarm to the traffic tower. The operator sets up audio and video communication with the bus to gain an overview of the situation and acts in relation to severity, such as calming down the passenger, stopping the vehicle and possibly dispatching paramedics to assist passengers.

Use Case: System detects that the vehicle needs assistance.
The last use case is more connected to the vehicle's ability to send relevant events to the traffic tower, where suitable actions can be taken by the operator or any automated handling of it.

Traffic tower for operation management of autonomous vehicles

In the Future 5G Ride project's last phase, Applied Autonomy came in to provide the traffic tower solution, denoted as xFlow®. The xFlow supports a transport operator's management process for autonomous shared vehicles. That includes remotely monitoring the vehicle fleet's driving states and deviations, providing driving tasks and assisting the passengers and vehicles. Reporting modules are available to provide insights into the operation.

Fig. 3. Overview of xFlow®'s integrations and main functionality.

In order to communicate with the passengers onboard the vehicle, the Future 5G Ride project has developed an onboard equipment for the bus, denoted "xFlow Edge", as a collaboration between Intel, Ericsson, Telia and Applied Autonomy. xFlow and xFlow Edge are visualised in Fig. 2.

AI detection and automatic alerts

For detecting the state of the passengers, the project has deployed a video analytics solution in the xFlow Edge. It was implemented using the OpenVINO toolkit which is an open-source toolkit that accelerates AI inference, using the trained AI model, with lower latency and higher throughput while maintaining accuracy and reducing model footprint. In the use case, we have used pretrained open source “body movement” models to discover if a passenger is potentially ill or needs assistance. For text to voice and vice versa we have been using the Whisper model.

All the models have been running on the Intel CPU and the GPU integrated in the CPU package. During the project Intel has launched new processors with integrated NPU’s (Neural Processing Units) . We have done initial testing with those and expect that we will be able to run multimodal models and consume less power in a smaller form factor than the previous solution.

Benefits of having AI acceleration hardware onboard:

- Security / privacy: Since the video data is analysed onboard the vehicle, the data stays on board and only the results of the analytics are being transmitted to the traffic tower, e.g., person laying down.
- Delay: Performing the video analytics in the vehicle reduces the delay compared to sending the data to be analysed at another location.
- Efficiency: When performing the analytics onboard, the traffic tower can be alerted very fast to minimise the impact of an incident/emergency.

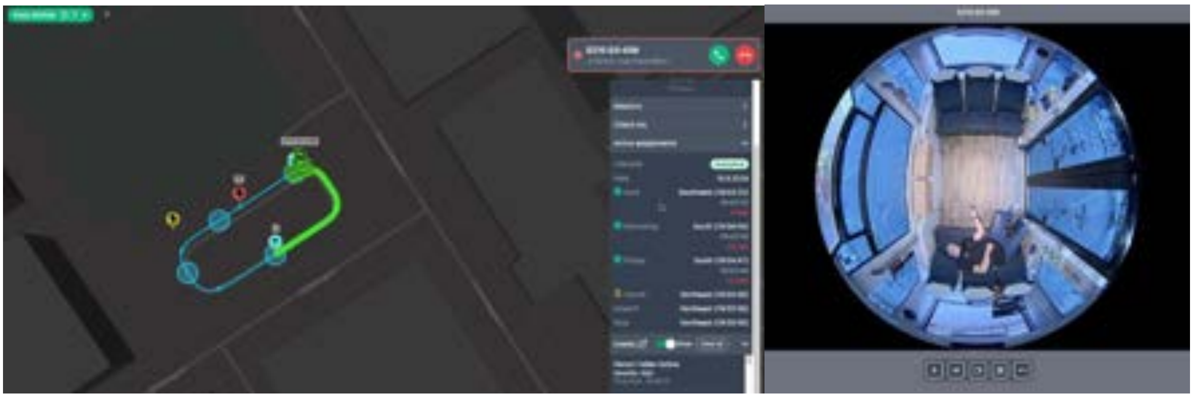


Fig. 4. Interfaces available to the remote operator.

The implemented solution as seen from the traffic tower is shown in Fig. 4. xFlow Edge has detected that someone probably has fallen and notifies the traffic tower operator, see the alert in the top right corner of the left picture in Fig. 4. Opening the call in the alert notification, confirms through the video that starts up that the passenger might need assistance.

5G and Quality on Demand in critical situations

All the functionality needed to safely manoeuvre the vehicle are located onboard the vehicle. However, as can be seen in Fig. 5, there are several communication needs between the autonomous bus and the traffic tower. Telemetry data like vehicle speed, position etc. are sent to the traffic tower for monitoring and decisions. Control messages can also be sent to the vehicle, e.g. updated route information. High quality video feeds can be sent from the vehicle so that the operator in the traffic tower can assess events that have occurred with the vehicle, or the passengers.

Most of this communication has rather relaxed requirements on the network. Most important is sufficient network coverage in the area the vehicles operate. Examples of more demanding use cases are temporary live video transmission from the vehicle and temporary remote driving. Note: Temporary remote driving was not a part of this project. It was implemented and tested in the previous project "5G Ride - Control Tower" [9].

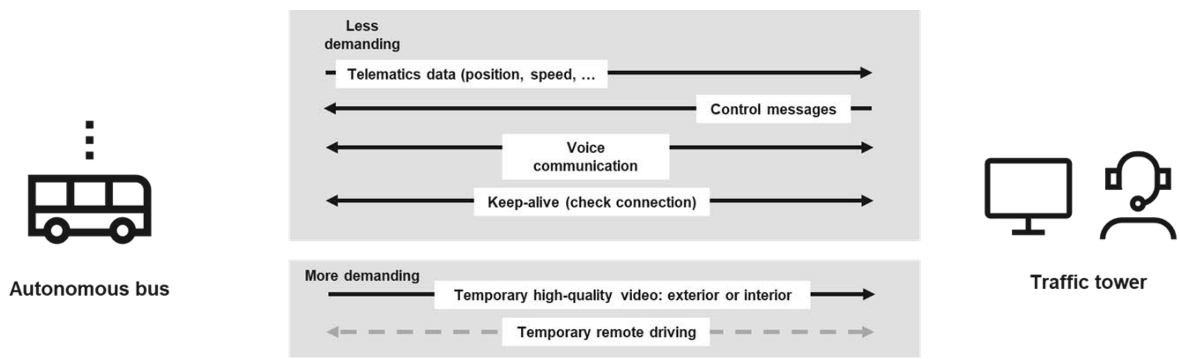


Fig. 5. Communication needs between the autonomous bus and the traffic tower.

Cellular network communication, to fleets of autonomous vehicles, is a necessity for the basic use cases of monitoring and dispatching vehicles. Video streaming from the vehicle to the traffic tower is not required all the time. It is only activated e.g., when a person in the traffic tower wants to assess an event that has occurred with the vehicle or the passengers. However, when it is needed, it is critical to get high quality real-time video directly, at that location and point in time. Data traffic from other users in the cellular network may vary based on time and location. Without Quality of Service (QoS) enabled all data streams are treated equally and at high load the quality of the video may then become degraded.

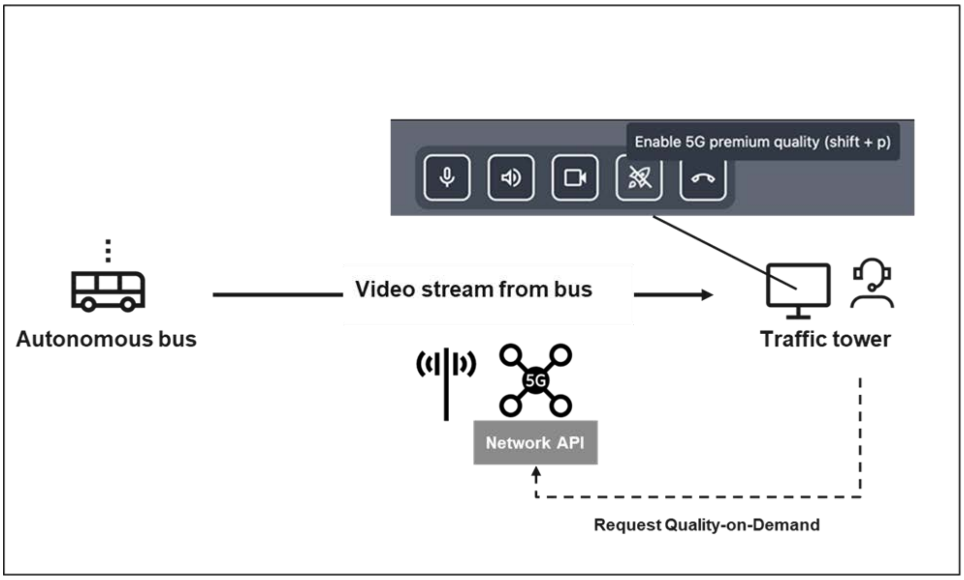


Fig. 6. Activation of QoS via QoD API.

A reliable 5G network with possibility to control QoS, along with hardware and software solutions in the vehicle and traffic tower open possibilities for transmission of high quality video streams. This capability has been built up and demonstrated in the Future 5G Ride project.

Fig. 6 illustrates the end-to-end solution implemented in the project. A person in the traffic tower can request premium quality from the 5G network, called Quality-on-Demand (QoD). It was shown that when QoD was activated, the video stream from the bus was unaffected even in an overloaded network. QoD is enabled by a very simple standardized API call (CAMARA[1] Quality-on-Demand API) sent to the 5G network. The key benefit for the owner of the fleet of buses is that they receive and pay for premium quality only when they really need it. The benefits for the mobile operator (e.g., Telia) is that they can monetize network resources by offering different quality-of-service profiles which can be dynamically consumed.

Demonstration of the solution in Kista Innovation Park, Sep 26, 2024

The xFlow Edge solution, including both the QoD button and AI activation, was mounted in the autonomous EZ10 shuttle from EasyMile, which was already integrated into the traffic tower, xFlow. The vehicle could be ordered to drive from station A to B on the demo track established in Kista. The traffic tower was manned by a traffic leader from Vy Buss AB. The different steps in the demonstration are described in Fig. 7.

[1] Camara Project – a Linux Foundation Project: https://camaraproject.org/

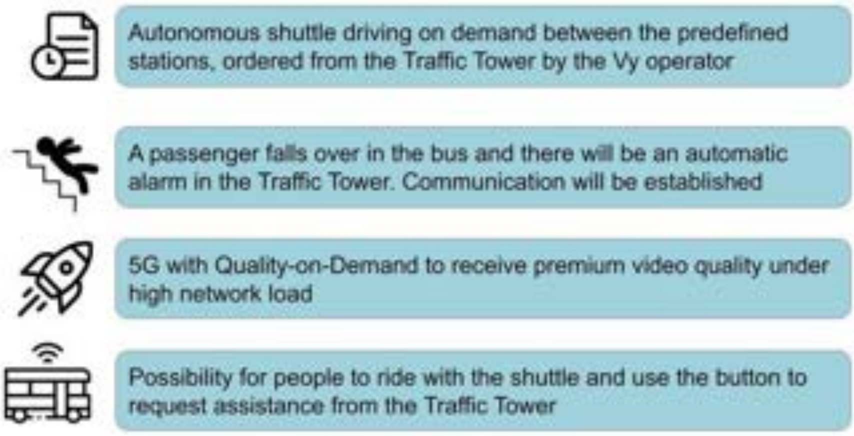


Fig. 7. The steps of the demo showed in Kista September 26, 2024.

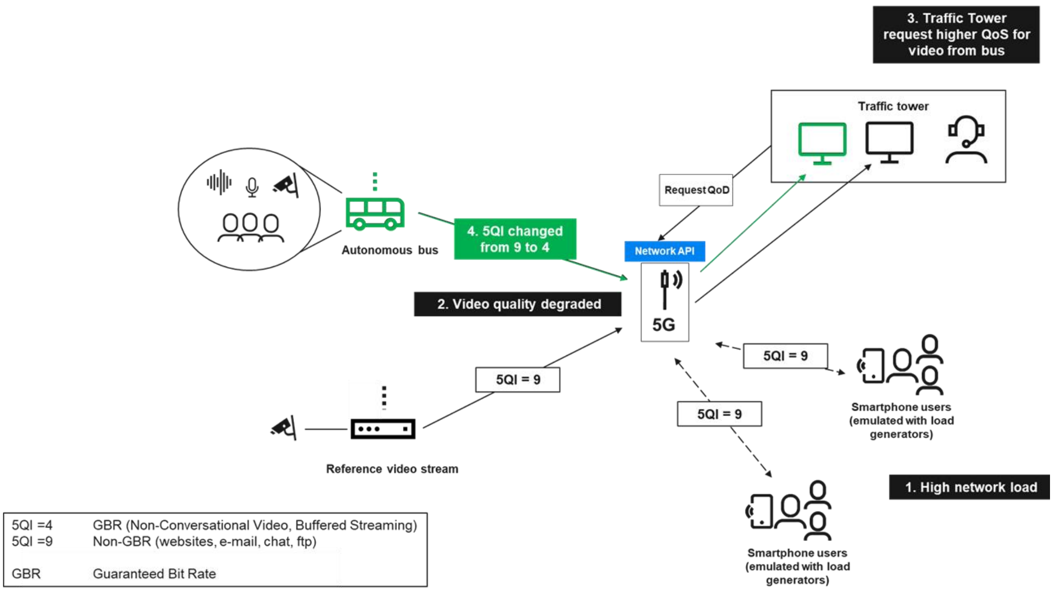


Fig. 8. QoD demo sequence.

Fig. 8 shows the demo sequence executed for QoD. At the start there were 2 video sessions ongoing; the video from the bus and one reference video stream. Initially all data streams are treated equally by the network, that is they are all assigned the same 5G QoS Identifier (5QI). In the demo we used 5QI = 9. In step 1 and 2, load generators overloaded the network with data traffic and it was seen that the video quality for both video sessions degraded. In step 3 the operator in the traffic tower pressed a button in the GUI of xFlow, which sent the QoD API call to the 5G network (step 3). This changed the 5QI from 9 to 4 for the video stream from the bus (step 4). 5QI = 4 means that the 5G network will provide a guaranteed bitrate for the video stream from the bus. It was shown that when QoD was activated the video stream from the bus was unaffected even in an overloaded network. This is illustrated in Fig. 9 where it can be seen that the reference video is still degraded, but the quality of the video from the bus is unaffected.

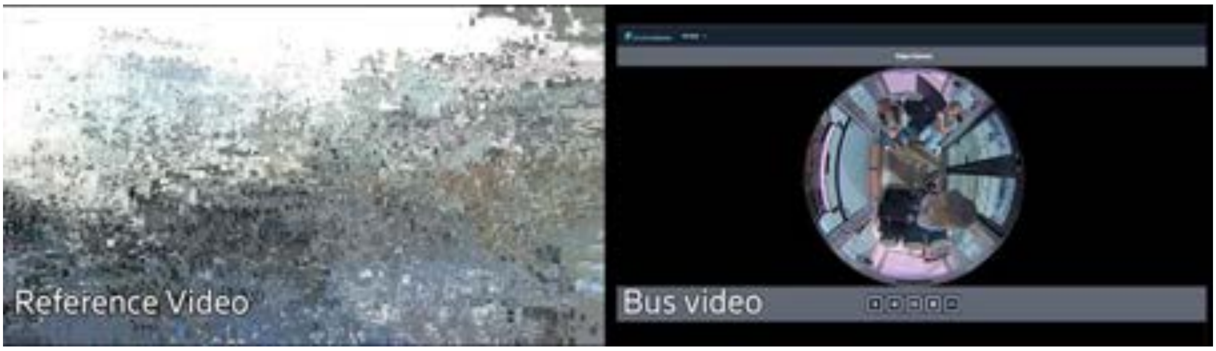


Fig. 9. Video quality during high network load with QoD activated for bus video.

5.3 Shared Situational Awareness and Collaborative Decision-making

No matter how many sensors that will be mounted on automated vehicles, there is the challenge that even the field of view of all sensors combined is limited. This makes some traffic situations difficult to solve, especially in urban areas. A common solution for the limited field of view is to reduce speed, which does not always improve the acceptance of automated systems by other road users. Another result can be sudden hard braking situations when the pedestrian is detected late, causing unsafe feelings for both passengers and the other road users in the vicinity.

Infrastructure sensors can be mounted along roads, around intersections, or at other locations that present challenges for on-board sensors due to occlusions, dense traffic or visual noise. They can be used to inform autonomous vehicles of objects or road users in the traffic environment that for various reasons are not visible to the vehicle's onboard sensors.

Using edge computing and smart infrastructure sensors, intelligent off-board systems can support traffic in a local area to enhance safety and improve road throughput. For example, with shared situational awareness, connected vehicles can cooperatively detect pedestrians, cyclists, and other vehicles and share relevant safety-critical information where direct line-of-sight is limited. This allows vehicles to navigate faster and more safely with real-time support from the connected infrastructure.

Another benefit of mounting smart infrastructure sensors in the environment is that they provide the means to detect area-specific behaviors. Vehicles are typically in any given location for only a few seconds. On the other hand, infrastructure sensors are able, throughout their lifetime, to detect and learn how road users behave. This makes it possible to do better predictions of future motion, to quickly identify anomalous behaviors, and to consciously direct attention to area-specific safety-critical situations. Moreover, such sensors can monitor the traffic flow disturbances and obstructions, like queues, broken vehicles or cars parked on the bus stop, which can in turn be used by the traffic tower to re-route the autonomous buses and efficiently avoid service disruptions.

To take advantage of the many benefits that intelligent off-board systems provide, there is a need for communication. Automated vehicles will need to exchange information with each other, infrastructure, and cloud services. This has led to the development of intelligent transportation system (ITS) technologies that utilize wireless technologies, including different varieties of dedicated short-range, direct communication, cellular 4G/5G for vehicle-to-everything (C-V2X) communication.

Although a direct connection between vehicles and infrastructure would be beneficial to reduce latency to an absolute minimum, many OEMs prefer the Extended Vehicle concept ISO 20077-1:2017. In the Extended Vehicle concept, a vehicle is connected to its own backend and secure connections to it are made through its backend. The main reason for this is to have the ability to monitor network traffic from external sources to the vehicle. This makes it possible to decide if a source is thrustful enough to use. To illustrate, Fig. 10 shows a simplified architecture of connected ITS applications similar to the Extended Vehicle concept. Notably, vehicles and local infrastructure can route their traffic through their own backends as described by the Extended Vehicle concept.

Developing future mobility applications requires deep understanding and scenario testing of integrated systems. To that end, this project set out to deploy ITS applications in practically relevant design architectures, such as Fig. 10, to study their benefits and constraints. Importantly, with new connections being made between vehicles, infrastructure and cloud, there is a need to understand how different forms of sensing and control are affected and enabled by the communication technology.

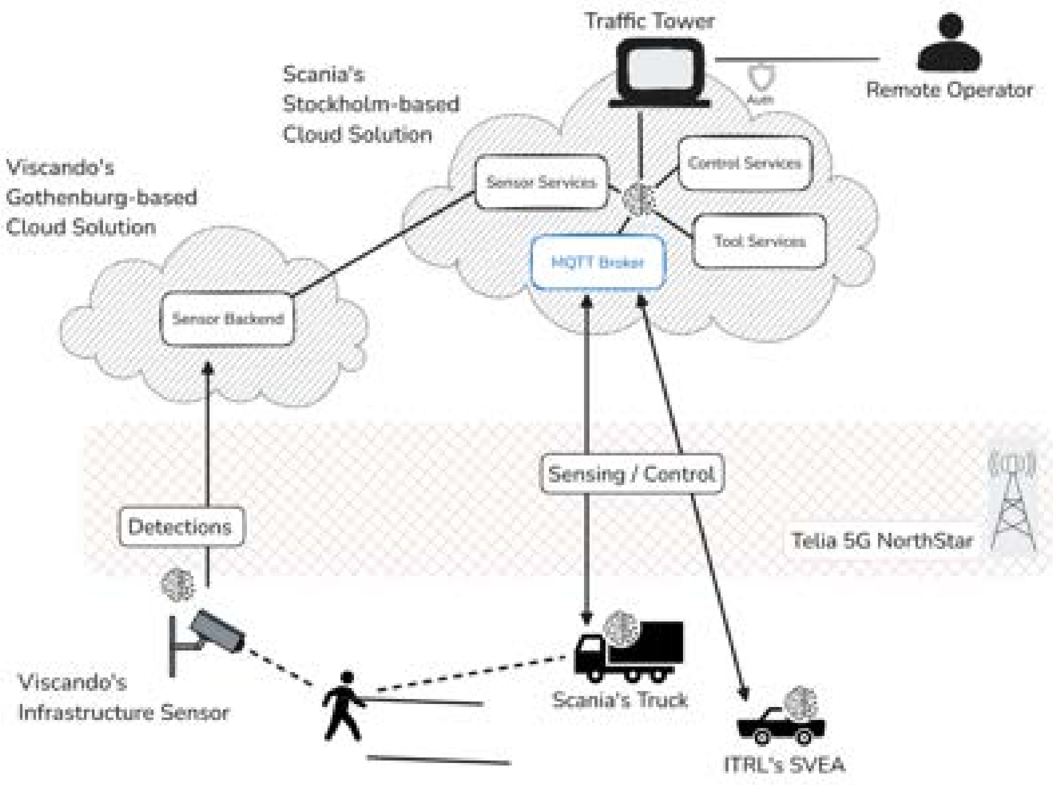


Fig. 10. Intelligent applications running on-vehicle, in the local infrastructure and in the cloud.

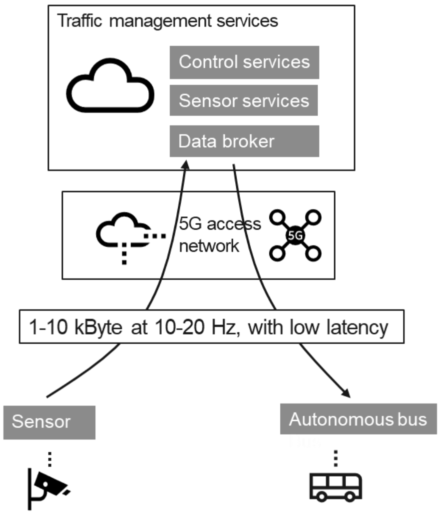


Fig. 11. Communication requirements for infrastructure sensors and autonomous vehicles.

Possibilities with 5G

The data packages sent from an infrastructure sensor are typically small, containing only coordinates and object classification, and need to be delivered at a given interval and with low latency. The detections are sent to a data broker that distributes this information directly to vehicles in the area or does further analysis and decision-making centrally. We refer to this collectively as traffic management services in Fig. 11 where we break down the communication requirements.

Depending on how the vehicle will use this information, the latency requirements on the cellular network vary. Factors like speed of vehicles and distance to detected objects also have an impact on the latency requirements. Moreover, considering the total end-to-end delay budget, ultra-low latency over 5G is not required since both sensors and vehicle will add relatively large computational latency. For example, the computational latency added by the sensor and vehicle can be in the range of 100-150 ms, respectively, while the one-way latency in a public, commercial 5G network is 10-20 ms.

It is, however, important that the latency is bounded and predictable also in a radio cell with load from other users. Consequently, there is a need to protect data traffic supporting advanced ITS applications so it is unaffected by eventual disturbances in the network.

5G offers Time Critical Communication (TCC) features that support use cases that need low and bounded latency. In this work, the 5G feature absolute priority scheduling was evaluated which gave sensor communication the highest priority in the network. The results from the tests showed that 5G is applicable for a wide range of the different infrastructure sensor use cases. However, given the total end-to-end delay budget, we envision that infrastructure sensors and collective perception will at first be primarily used for proactive measures, e.g., adapting speed and direction to avoid conflicts from happening, rather than emergency manoeuvres in near-collision situations. Such measures typically have a time horizon of several seconds while, for the latter ones, perception, decision and reaction must happen within several 100 ms. Hence, information from infrastructure sensors should currently be seen as a complement to the vehicle's on-board sensors to improve comfort and efficiency, rather than safety applications.

Tests have shown that future distributed solutions need accurate time synchronization to secure a common time reference between all parties. 5G includes such features (NR SIB9, PTP etc.) and can distribute time synchronization within µs level. GNSS-RTK data can also be distributed via the 5G network for more accurate positioning of the vehicle. Such functionalities would be of interest to include in future work within this area.

Integration of Testbeds and Research Environments

While there are some preliminary studies on C-V2X using 5G, many of the studies conducted so far have been developed around 4G. This can be attributed to the current difficulty around prototyping advanced ITS applications in a controlled environment with a real 5G network, hardware, and software in the loop. By collaborating on partners' testbeds and research environments, this project has been able to do early evaluations of future mobility applications.

Specifically, we have used a test methodology, outlined by Fig. 12, that enables low-cost experimentation on advanced C-V2X applications with the ability to precisely evaluate the 5G cellular network, hardware, and software's performance. Testing is first conducted in small-scale deployments to understand problem and solution domains, implications of architectural design, and to collect initial insights of application performance. This step promotes partners to explore together and align on technical goals. Next, full-scale tests are conducted in controlled research environments at closed test tracks. Now, partners can develop their individual technologies and do early integration. With these collaborations, research ideas get better prospects of reaching the market. In this project, we have successfully carried out tests in the first and second steps.

Fig. 12.   Testing is first conducted in small-scale deployments, then in full-scale tests at closed test tracks. Finally, this accelerates the development cycle and improves prospects of research ideas getting to market.

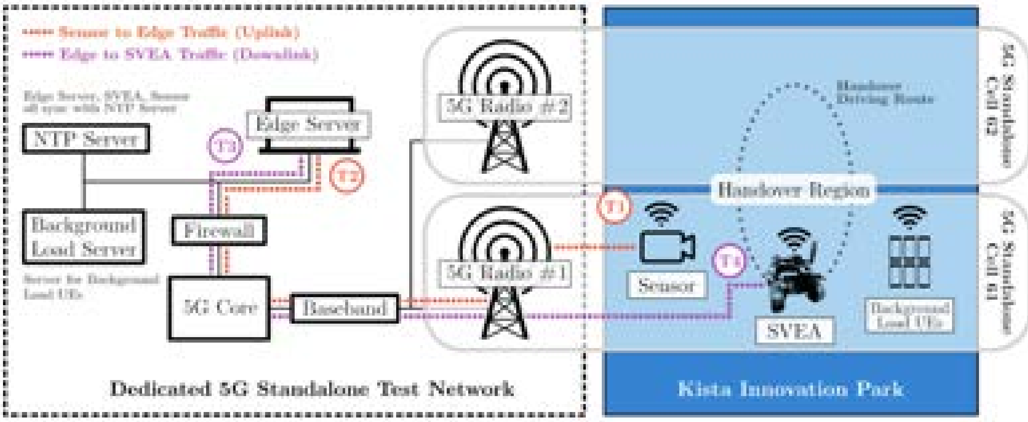


Fig. 13. Test set-up with Ericsson's private 5G SA network in Kista, see [1] for details.

Kista Tests

To make experimentation faster and cheaper, KTH modified their 1/10th-scale Connected and Automated Vehicle (CAV) platform to evaluate C-V2X . Although small-scale CAVs do not capture the full dynamics of full-scale CAVs, they do provide the ability to cheaply evaluate V2X applications with real network, hardware, and software in the loop. Additionally, small-scale CAVs offer the ability to do preliminary studies with motion, providing some initial insight into how the results translate to full-scale CAVs. The small-scale CAV platforms implement their 5G C-V2X applications using the Robot Operating System (ROS). The use of ROS yields significant development benefits, as it provides wide, open-source support for most of the sensor and message types that are required in C-V2X applications. For example, there exists support for ETSI ITS messages in the ROS ecosystem. However, since ROS is a best-effort implementation, there should be some consideration on how to implement and evaluate message passing, time synchronization and such.

Together with Ericsson tests were performed in Ericsson's private 5G SA (stand-alone) network in Kista. To fully evaluate a 5G C-V2X application, it is necessary to recreate real-life conditions that impact the cellular network. With Ericsson's 5G SA network, we were able to precisely modify background load and test features that protect traffic. It is important to investigate the trade-offs related to network performance as it is not only influenced by the traffic volume but also by the number of users, the direction of the traffic, and the configuration of the network. The network had a 20 MHz bandwidth and used a Time Division Duplex (TDD) pattern with downlink/uplink resource ratio of 3/1. Lastly, in the context of our scenario, we utilized a specific QoS mechanism in the 5G radio access network called absolute priority scheduling.

The Kista tests aimed to emulate a practically relevant ITS scenario such as the one outlined in Fig. 10. The goal was to investigate what features a 5G cellular network could use to improve the communication conditions shown in Fig. 11. The tests were set up as described by Fig. 13 to test the absolute priority scheduling for traffic, handover events, and safety implications of a highly loaded network. The results were published in [1].

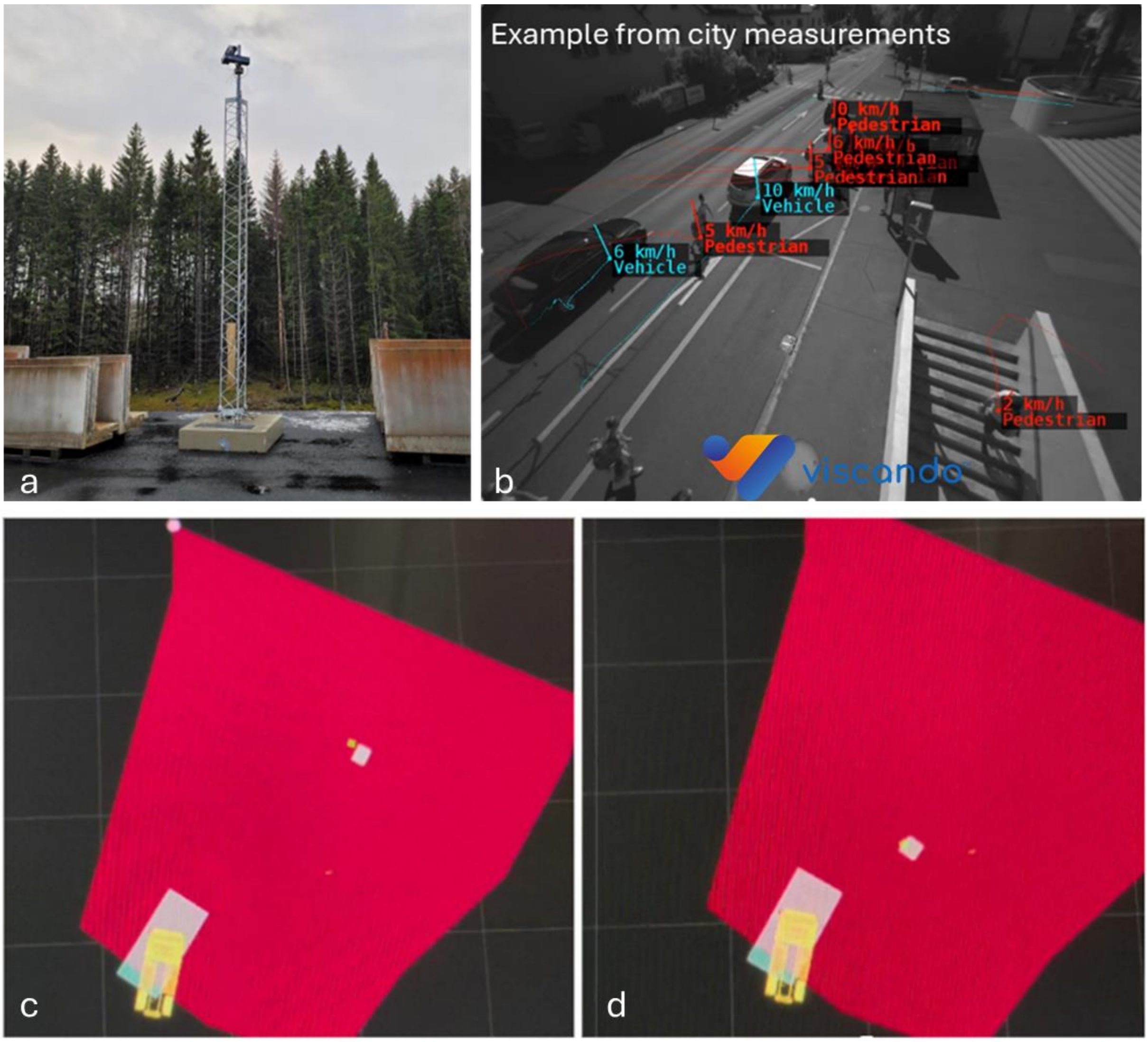


Fig. 14. (a) Viscando sensors installed on Scania's test track. (b) Example of Viscando object movement data from a city measurement. (c,d) Pictures showing a pedestrian moving around in circles in front of a Scania truck. The pedestrian as detected by the truck is shown in white. The position of one of Viscando's infrastructure sensors is marked by the top-left circle in pink, with its detection range shown in red. On the left, a sudden change in direction of the pedestrian is causing the detections to deviate, showing the need for shared situational awareness to improve collective perception.

Södertälje Tests

Similar tests were also performed at Scania in Södertälje over both Telia's public 5G NSA (non-stand-alone) network and a 5G SA network (Telia NorthStar). While the Kista tests were highly focused on the technical aspects of 5G C-V2X communication, the Södertälje tests focused more on general exploration of the Extended Vehicle concept. Unlike in Kista, where sensors sent mock data and the server was hosted on-site, the Södertälje tests used the full-scale deployments of Fig. 10.

Specifically, we demonstrated shared situational awareness with a Scania truck's own onboard sensors and detections from two of Viscando's infrastructure sensors, see Fig. 14. Viscando sensors, shown on Fig. 14a, detect, classify and track all types of road users in real time (example from an urban scene is shown in Fig 14b). The object data, which is fully anonymized and therefore GDPR compliant, is transmitted on the 5G network.

On the Scania test track, a pedestrian was moving around in front of the truck. Using the full onboard sensor suite, the truck could track the pedestrian as long as it was in the vehicle's field-of-view. At the same time, Viscando's sensors published their sensing data of the pedestrian to Scania's backend, in effect extending the truck's field-of-view, as shown on Fig. 14c,d. The external sensors had been calibrated using RTK-GNSS measurement equipment, allowing the vehicle to receive the pedestrian's position in global WGS 84 coordinates. The truck could then convert the coordinates to its own local coordinate reference system.

The Södertälje tests demonstrated the capabilities of commercially-available products deployed in an industrially-relevant C-V2X architecture. Notably with real sensor data being sent to, and processed by, Scania's backend services that were hosted on Stockholm-based servers. All agents, i.e. truck and infrastructure sensors, were connected to Telia's public NSA 5G network, and later, Telia 5G SA network NorthStar. As seen in Fig. 14, the detections from on-board sensors and infrastructure sensors align spatially very well, within 50 cm, with respect to the scenario. The total computation and communication latency of approximately 200 ms, from that of Viscando's sensor capturing the image to Scania's truck receiving the detection, also indicate readiness for certain use-cases.

In practice, a grid of multiple infrastructure sensors can be deployed to extend vehicles' field-of-view over large areas. By installing them 4-12 meters above ground, infrastructure sensors avoid many of the occlusions compared to the on-board sensors, which is especially important in dense urban scenarios. Images are quickly processed and permanently removed within 20 ms after each capture, then storing and sending only anonymized trajectories of perceived road users. This ensures full GDPR compliance and possibility to deploy on both high-security areas like test tracks and on public roads.

The full-scale demonstration has shown that it is feasible to create highly reliable and low-latency communication channels between different actors in the transport system. Even if this channel is realized between backend services instead of point-to-point, the performance is still comparable to onboard sensors. The latency due to communication is a relatively small part of the total processing time. A stable and predictable latency is more important than extremely low latency.

6. Results and Deliverables

The project has achieved the goals that were set for each work package and gathered valuable insights for potential next steps. Deeper insight has been acquired both in understanding parameters affecting user experience as well as safeguarding passengers through actions by the AI or in contact with the traffic tower. The ability to "see around corners" with the help of infrastructure sensors has been showcased and values connected to a more efficient and safe transport system have been identified. The results have been verified as well as knowledge spread about the results by showcasing and demoing the project's achievements to reference groups and the public. For this test sites in Kista and Södertälje have been used. A result of a multi actor project group with engagement in Sweden the knowledge base of relevant actors in a future scaled solution in Sweden is elevated.

6.1 Insights and Key Learnings from Project Activities

User Acceptance of Automated Vehicles in Public Transport

For passengers the experience of safe and secure traveling can be achieved. Through different analyses the project has tested the acceptance of riding in an autonomous vehicle and found it to be a positive acceptance.

With autonomous vehicles and control centers the professional role of the driver, and other positions, will change. There will be a more controlled environment to work in, for temperature reasons as well as safety. Being a driver on distance as support will also give the possibility to have breaks and do toilet visits when needed.

Safeguarding passengers using AI and 5G in autonomous buses

The project delivered and demonstrated a mobility concept that supports supervising a fleet of autonomous vehicles with no safety driver on board. Through the traffic tower, both the vehicle and the passengers could be assisted from remote to ensure safe and efficient transport operation. AI models executing on an edge solution inside the vehicle, were used to detect abnormalities on board and to alert the remote operator in the traffic tower. The framework is prepared for new models in the future. High quality video communication on the 5G network between the vehicle and the traffic tower during high network loads was implemented as a Quality on Demand function.

Integration of Testbeds and Research Environments

Testing ITS applications is favorably done through simulation, small-scale deployments and full-scale tests. With industrial and academic collaboration, these steps further accelerate cost-effective evaluations of 5G network, hardware, and software performance, which generate new research and develop innovation that eventually lead to market readiness.

Kista Tests

Using KTH’s 1/10th-scale CAVs, the Kista tests evaluated 5G features like absolute priority scheduling in Ericsson’s private network. These tests emulated relevant communication scenarios, focusing on traffic management and network performance under load, revealing valuable insights into trade-offs in network configurations.

5G was shown to be applicable for a wide range of the different infrastructure sensor use cases. Ultra-low latency over 5G is not required since both sensors and vehicle will add relatively large computational latency, but bounded and predictable latency also in a loaded network is needed. The 5G Time Critical Communication (TCC) feature absolute priority scheduling provided low and bounded latency.

Södertälje Tests

Full-scale tests in Södertälje integrated Scania trucks, Viscando infrastructure-based 3D&AI sensors, and Telia's 5G networks to demonstrate shared situational awareness. Infrastructure sensors extended vehicle perception, showing precise spatial and temporal alignment with onboard data, while ensuring GDPR compliance and robust real-world applicability.

6.2 Review of Outcomes and Technology Readiness

For evaluation the Technology Readiness Level (TRL) was used connected to the goals. The scale defines 9 levels of readiness. With the reference to the scale of Technology Readiness Level(TRL), work packages developing the traffic tower, delivering a connected and autonomous vehicle, passenger perceived safety all achieve a TRL level of 6 or higher which correlates to System/process prototype verified in demonstration in an operational environment (beta prototype system level). The ingoing systems safeguarding passengers reached between 6-8 where 8 is a commercially ready system. For situational awareness a goal of elevating the readiness to TRL 5 was achieved which correlates to Laboratory testing of Integrated/Semi-Integrated System: System Component and/or process validation is achieved in a relevant environment.

7. Lessons Learned and Next Steps

The project has along the way changed the platform for the traffic tower, involved operator as well as provider of the autonomous vehicle and still managed to achieve the goals of the project. In complex iterative innovation projects like the Future 5G ride project, this is a plausible scenario which has given the project more perspectives and input to the solution. Due to good project planning as well as redundancy in the project, challenges were mitigated. A shorter project period could have inflicted on the possible final result. Bringing complementary companies together in such an ecosystem, generated probably a better solution with lower risk for the parties and a possible customer.

During the project an idea of delivering autonomous transport test rides on public roads was discussed. However, due to change in actors in the project delivering the autonomous vehicle and long process period to acquire permits, the focus was shifted making it a possible follow up project. Apart from the permit, the set up of the project enabled valuable insight in scaled solutions on public roads and through the access to physical test beds were able to showcase equivalent demonstrations.

As development of autonomous transport accelerates, connectivity leads to new collaborative technologies that improve safety, efficiency, and sustainability. With control and estimation algorithms at the edge of a cellular network, it is possible to leverage higher compute capabilities while retaining low communication latency. Combined with guarantees from 5G QoS-features, as have been shown in Future 5G Ride, this enables traffic infrastructure to take a more active role in transportation. Ultimately, future work should aim to identify control algorithms, communication architectures and ITS services that have a meaningful impact on autonomous transport.

It is generally considered that the most serious traffic accidents occur on high-speed roads without protective barriers between directions, whereas most traffic incidents happen at lower speeds in urban areas. Automated vehicles are already used today in various environments, but large scale deployment is impeded by the risk of long-tail development. This is due to the extensive amount of edge-cases that occur in traffic, especially in highly dynamic urban environments with mixed-traffic, i.e. traffic with road users of varying degrees of automation and connectivity . A number of methods have been developed in research to address this issue by providing formally proven, strong safety guarantees. To overcome the risk of long-tail development, further research is required on how such safety systems should integrate with ITS and the transportation system as a whole.

With this project’s foundation in public transport, we especially promote further research around the particular challenges found at transport sites such as bus terminals, electric charging pools, etc. Transport sites like these inherently involve more complex behavior and dynamic interactions. During the transition to fully autonomous traffic, these sites will prove to be increasingly important as vehicles of different automation levels, connected transport infrastructure and vulnerable road users must interact and coexist. They will also play a major role in improving the efficiency and sustainability of the transport system as these sites typically constrain traffic, for example due to mutually exclusive infrastructure (e.g. only one vehicle can charge at a charging station at a time).

To address these challenges, inspired by the outcomes of this project, one can consider supporting automated vehicles at critical transport sites with centralized traffic services It is wise to learn from and test on regional/local actors, systems and behaviour, but it might be a cost driver for scaling up the transport solution since there might be a lot of one - of - a - kind integrations. Learning for improved standardisation is crucial for business scaling where the same solution is sold several times.

Advanced ITS systems must align constraints and goals from all levels of operation, whether it is from fleet-wide charging schedules, coordination of vehicle movements at the local site, or management of passenger boarding. Future work includes researching what types of services a transport site could host and how such system integration and alignment should be done.

The results from the project shows that 5G capabilities and features are sufficient to support the communication needs of autonomous vehicles. However, sufficient network coverage in the area where the vehicles operate needs to be secured. Therefore as the scale up of fleets of fully autonomous vehicles happen, corresponding ramp up of 5G network infrastructure along roads is essential.

Finally, feedback from demonstrating the passenger assistance solution, indicates that it is relevant and valuable for the scale up of fleets of fully autonomous vehicles. A commercial solution will be the next step. The learnings and solutions from 5G Ride will be used in the upcoming Swedish projects in Sälen and Gothenburg where large sized autonomous buses will be used in public transport.

8. Conclusion

Sensors in the infrastructure can assist the vehicle in certain situations that are difficult to solve otherwise. The 5G mobile network makes it possible to share data between the infrastructure mounted sensors and the vehicle with a latency that is comparable to the onboard sensor processing.

A traffic tower solution is required that supports a transport operator's management process for autonomous shared vehicles. The solution includes remotely monitoring the vehicle fleet's driving states and deviations, providing driving tasks and assisting the passengers and vehicles. A reliable 5G network with possibility to control QoS, along with hardware and software solutions in the vehicle and traffic tower open possibilities for transmission of high quality video streams. QoS can be activated on demand with a very simple standardized API call (Quality-on-Demand) sent to the 5G network.

The autonomous technology by itself gives the possibility to reduce emissions and accidents, as well as increasing efficiency. Using autonomous technology gives the possibility to improve transportation possibilities in completely new ways. If we take care of different possibilities provided by technology development and embrace the change of usage made possible, it really can make a big difference for the society.

However, depending on how the new possibilities are implemented and used the amount of transports, and thereby effect on congestion, can be both better and worse. If autonomous vehicles are used for shared transportation of goods and people, calculations show that it will decrease congestion, decrease the necessary number of vehicles and thereby also decrease the needed amount of land area used for the existing transportation system.

9. Dissemination and Publications

Seminars and demos

Mobility Day June 2022 - Press and ecosystem invited to presentations and demonstration of the Future 5G ride project among other projects and discussions.

Demo day October 2022 - Press and ecosystem invited to presentation and demonstration project progress. Opportunity to see and ride along in the autonomous vehicle.

ITS November 2022, presentation of the project.

Demo day September 2024 - Press and ecosystem invited to presentation and demonstration project progress. Opportunity to see and ride along in the autonomous vehicle.

Ny Teknik Education i samarbete med FFI Webinarium 2025 – Paneldialog ”Trafiksäker automatisering av transporter – är det möjligt?”

Publications

5G Ride film 2024 – video about the project produced jointly by all the partners during September 2024

5G Ride project paves the way to better public transport – article on www.ericsson.com about the 5G Ride event in Kista September 26, 2024

News articles about the 5G Ride event in Kista September 26, 2024.

- Ericsson: Så möjliggör 5G autonoma transportsystem
- Ett steg mot förarlösa bussar

Seeing through obstacles and around corners, the 5G Ride project rolls on – Kista Science City article about the 5G RIDE Demo Day in Kista on October 13, 2022

News articles about the 5G RIDE Demo Day in Kista October 13, 2022

- 5g-bussen upptäcker ”osynliga” trafikfaror runt hörnet
- Här provåker vi 5g-ride-bussen i Telias 5g-nät
- Självkörande och elektrisk – framtidens kollektivtrafik tas fram i Kista

Fokusgrupper på temat trygghet ombord på en förarlös buss, VY buss och Couple Consulting, november 2024 [10]

Scientific Dissemination

Conference articles: [1-5].

Master Theses: [6] and [7].

PhD Theses: [11].

10 References

[1] Arfvidsson, Kaj Munhoz, Kleio Fragkedaki, Frank J. Jiang, Vandana Narri, Hans-Cristian Lindh, Karl H. Johansson, and Jonas Mårtensson. "Small-Scale Testbed for Evaluating C-V2X Applications on 5G Cellular Networks." In 2024 IEEE Intelligent Vehicles Symposium (IV), 149–55. Jeju Island, Korea, Republic of: IEEE, 2024. https://doi.org/10.1109/IV55156.2024.10588559.

[2] Arfvidsson, Kaj Munhoz, Frank J. Jiang, Karl H. Johansson, and Jonas Mårtensson. "Ensuring Safety at Intelligent Intersections: Temporal Logic Meets Reachability Analysis." In 2024 IEEE Intelligent Vehicles Symposium (IV), 292–98. Jeju Island, Korea, Republic of: IEEE, 2024. https://doi.org/10.1109/IV55156.2024.10588818.

[3] Arfvidsson, Kaj Munhoz, Frank J. Jiang, Karl H. Johansson, and Jonas Mårtensson. "Towards Safe Autonomous Intersection Management: Temporal Logic-Based Safety Filters for Vehicle Coordination." arXiv, August 27, 2024. http://arxiv.org/abs/2408.14870.

[4] Jiang, Frank J., Kaj Munhoz Arfvidsson, Chong He, Mo Chen, and Karl H. Johansson. "Guaranteed Completion of Complex Tasks via Temporal Logic Trees and Hamilton-Jacobi Reachability." arXiv, April 12, 2024. http://arxiv.org/abs/2404.08334.

[5] Fragkedaki, Kleio, Frank J. Jiang, Karl H. Johansson, and Jonas Mårtensson. "Pedestrian Motion Prediction Using Transformer-Based Behavior Clustering and Data-Driven Reachability Analysis." arXiv, August 9, 2024. http://arxiv.org/abs/2408.15250.

[6] K. M. Arfvidsson, "Formal Verification of Regional Rules for Connected and Automated Vehicles," M. Sc., KTH Royal Institute of Technology, 2024.

[7] A. Wong, "Cooperative Localization at Intersections," M. Sc., KTH Royal Institute of Technology, 2025.

[8] E. S. Turah *et al.*, "5G Ride," Drive Sweden, Mar. 2021. Accessed: Jan. 15, 2025. [Online]. Available: https://www.drivesweden.net/sites/default/files/2021-11/final_report_5g_ride_2020_1.1.pdf.

[9] E. S. Turah *et al.*, "5G Ride Control Tower," Drive Sweden, Nov. 2022. Accessed: Jan. 30, 2025. [Online]. Available: https://kista.com/wp-content/uploads/2025/01/Final_report_5G_ControlTower_220114.pdf.

[10] Vy Buss och Cupole Consulting Group, "Future 5G Ride: Fokusgrupper på temat trygghet ombord på en förarlös buss." Accessed: Jan. Feb 5, 2025. [Online]. Available: https://kista.com/wp-content/uploads/2025/02/Report-Focus-groups-Safety-on-board-of-driverless-buses.pdf.

[11] S. Dolins, "Together, We Can Get Somewhere: exploring potential factors for the implementation of shared, autonomous public transport," 2024. Available: https://research.chalmers.se/publication/543874.