

SAFE TUNNELS FOR SMART VEHICLES: CHALLENGES AND OPPORTUNITIES OF AUTOMATED DRIVING IN ROAD TUNNELS

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ABSTRACT

The digitalization of traffic infrastructure is a key enabler for connected and automated driving. Automated vehicles will increasingly interact seamlessly with infrastructure, offering significant potential to reduce accidents and enhance both safety and road capacity. However, tunnels present unique challenges due to their specific safety requirements and the absence of Global Navigation Satellite System (GNSS) signals, which complicates accurate vehicle localization. Radio-based positioning systems also face issues such as multipath propagation caused by reflections in tunnel environments. Current solutions focus primarily on vehicle-based sensors, but these have limitations in tunnels. The research project AUDIT analyses localization by vehicle-based sensors as well as Cooperative Intelligent Transport Systems (C-ITS), which enable continuous bidirectional data exchange between vehicles and infrastructure. Safety impacts are assessed using systematic risk analysis methods, considering Society of Automotive Engineers (SAE) automation levels and mixed traffic scenarios. The project also discusses the effects on tunnel operations under both normal and emergency conditions from the operator's as well as tunnel user's perspective. Feasibility studies in Austrian and German tunnels will validate promising technologies for supporting automated driving in road tunnels. A dedicated test vehicle equipped with multiple sensors and communication modules collects comprehensive data to evaluate positioning accuracy and communication reliability. The findings will provide recommendations for sensor configurations, infrastructure adaptations, and operational protocols, including cost-benefit considerations. Ultimately, the project aims to provide actionable solutions for safe and efficient automated driving in tunnels, contributing to the development of unified standards and best practices for integrating automated vehicles into future transport systems.

Keywords: road tunnel, automated driving, C-ITS, tunnel safety, risk assessment, localization in tunnels

1. BACKGROUND AND MOTIVATION

The ongoing advancement of digitalizing traffic infrastructure is a crucial prerequisite for connected and automated driving. Automated vehicles will become an integral part of a system characterized by seamless interaction between vehicles and infrastructure. This development offers the potential to reduce accidents and significantly improve both traffic safety and road capacity [1].

Tunnels, due to their specific conditions, present a unique challenge that must be addressed from both the perspective of the vehicle and the infrastructure. Additionally, tunnels themselves have specific safety requirements due to additional risks in case of accidents or fires. Accurate positioning and localization of vehicles are crucial for automated driving. However, due to the lack of GNSS signal coverage in tunnels, this cannot be easily achieved. In Alpine regions as well as in big cities, the widespread presence of tunnels or urban canyons poses challenges for automated driving.

The research project "Artificial Intelligence for Improving the Safety of Tunnels and Tunnel Control Centers (KITT)" [2] has demonstrated that the collection of vehicle-generated data using C-ITS can improve preventive safety and the availability of road tunnels. However, this requires precise positioning and localization of vehicles within the tunnel. Current C-ITS modules utilize GNSS for this purpose. It was found that signal loss currently causes the On-Board Unit (OBU) installed in the vehicles to cease sending further C-ITS messages – even those for which the exact vehicle position is irrelevant. In order to fully utilize the advantages of C-ITS in road tunnels, further research is needed regarding the positioning and localization of vehicles within tunnel structures.

This paper describes the current findings and ongoing research within the project “Automated Driving in Road Tunnels (AUDIT)” with its main objective to identify the challenges related to automated driving in road tunnels, focusing on lessons learned from KITT, and to develop solution approaches. This involves evaluating the suitability and system limitations of localization and positioning systems currently used in vehicles, as well as communication technologies between vehicles and infrastructure. Infrastructure-related challenges and measures to support vehicle localization and communication in tunnels are also examined and assessed based on cost-benefit criteria.

This research is funded by the Austrian Research Promotion Agency (FFG) under the “DACH Transport Infrastructure Research Call 2024” as part of a cross-border initiative for applied R&D services, supported by national public authorities in Austria and their representatives in Germany and Switzerland.

2. FUNDAMENTALS

2.1. Automated driving

Automated driving refers to the capability of a vehicle to operate and navigate without human input by using a combination of sensors, cameras, radar, Artificial Intelligence (AI), and Machine Learning (ML) algorithms. These systems allow the vehicle to perceive its environment, make decisions, and control driving functions such as steering, braking, and acceleration [3].

The degree of automation in a vehicle’s driving system can be described by the SAE Levels. They define six stages (Level 0 to 5), describing the transition from conventional driving to fully autonomous vehicles and regulating how driving tasks are distributed between human

and system. In Ref. [4] a seventh level, namely the L2+/++, is introduced. The six SAE-Levels named in [3] in combination with the intermediate level L2+/++ [4] are defined as follows:

- **Level 0 – no automation:** The human driver fully controls the vehicle and there are no automated driving functions, only warning systems may be present.
- **Level 1 – assisted driving:** Individual assistance systems such as cruise control or lane keeping assistant support the driver in specific tasks (longitudinal **or** lateral control). Full responsibility remains with the driver.
- **Level 2 – partial automation:** The vehicle takes over both longitudinal **and** lateral control under certain conditions (e.g., traffic jam assistant). The driver must monitor the system and be able to intervene at any time.
- **Level 2+/++ – advanced partial automation:** Navigation on autopilot. The driver must be able to immediately take full control whenever requested.
- **Level 3 – high automation:** The driver can temporarily hand over the driving task to the system and engage in other activities, as long as the vehicle operates within domain limits. The system independently recognizes its domain and prompts the driver to take over in good time.
- **Level 4 – full automation:** The vehicle drives completely autonomously in certain operational areas (e.g., highway, parking garage). The human becomes a passenger and does not need to intervene. If the system leaves its domain, it brings the vehicle to a safe state.
- **Level 5 – autonomous driving:** The vehicle takes over all driving tasks under all conditions, even in complex situations. There is no longer a driver, only passengers. Responsibility lies entirely with the system or manufacturer.

Automated vehicles can significantly increase traffic safety and efficiency. They reduce accidents, optimize traffic flow, and enable precise management of emergency situations. However, as the degree of automation increases, so do the requirements for sensors, communication, and positioning [1].

2.2. Vehicle-based sensor systems

Modern vehicles incorporate a diverse array of sensors designed to enhance driver assistance, safety and comfort. The following section examines the specific roles these in-vehicle sensors play in automated driving, with particular attention to their limitations within tunnel environments, [5].

Cameras are used to detect and classify objects, estimate distances, and recognize traffic lights, lane markings, and obstacles. However, their effectiveness is significantly reduced in adverse weather conditions such as rain or fog. In tunnels, varying light conditions as well as reflections from tunnel walls further impair camera performance, disqualifying their exclusive usage for vehicle localization in these environments.

The functionality of **Light Detection and Ranging-Systems (LiDAR-Systems)**, however, is more sophisticated in changing light conditions in tunnel environments due to the usage of laser beams to construct high-definition 3D maps of their surroundings. Yet, this systems are more expensive than cameras and have limited functionality in bad weather conditions such as rain or snowfall, [6].

Installed **Radar-Systems** are using long range radio waves for tracking objects and for measuring both their distance and velocity relative to its position. This system is independent of weather as well as light conditions. Radar information is used in technologies such as automatic cruise control, automatic emergency breaking or blind spot monitoring. However,

due to its large wavelength, the resolution is low and often contains noise leading to high uncertainties.

GNSS technology is a cornerstone for vehicle localization in the open, offering centimeter-level precision when enhanced with methods like real-time kinematics. However, in environments such as urban canyons and tunnels, GNSS signals are often obstructed or lost, resulting in unreliable positioning. When GNSS connectivity is interrupted, C-ITS messages are automatically deactivated, preventing C2X communication [7].

Inertial measurement units (IMUs), which include accelerometers and gyroscopes, track linear acceleration and rotational movements. Despite their high precision, IMUs accumulate small errors over time, making additional navigation systems necessary for accurate localization. Integrating GNSS data and employing AI-based error correction – through sensor fusion – significantly improves localization accuracy in road tunnels and urban canyons.

2.3. Connected driving

Apart from the above-mentioned vehicle-based sensor systems and the specification of their requirements and application possibilities, this project aims to additionally place a strong emphasis on C-ITS technology. The key to ensure safety, efficiency and environmental sustainability in the modern transport sector is communication – the communication among vehicles and the communication between vehicles and infrastructure. C-ITS is an initiative in this regard and enables communication in real time.

In vehicle-to-everything (V2X) and cellular-V2X (C-V2X) communication, access technologies such as ITS-G5, Long Term Evolution (LTE-V2X) and 5G new radio (5G NR-V2X) within the 5.9 GHz frequency band are used. In KITT [2] it was determined, that in road tunnels the infrastructure transmitters, the so-called Roadside Units (RSUs), must be installed approximately every 300 m to enable continuous monitoring.

RSUs in tunnels communicate event-based information, for example a breakdown, in real-time via Decentralized Environmental Notification Messages (DENM) while information about vehicle status or its exact position is continuously transmitted via Common Awareness Messages (CAM). All this information can be used to reduce accidents, optimize traffic flow, and enable precise management of emergency situations. However, one of the major findings of KITT was that, due to the absence of GNSS signals, currently installed C-ITS systems cease all functions and no messages are sent or received. For this reason, C-ITS can currently not be used in tunnels. Either the infrastructure must provide a GNSS signal coverage or vehicle-side OBU systems have to be adapted.

2.4. Infrastructural localization systems

Ref. [8] identified ideal routes in the Swiss road network for future, initial test applications under real-world traffic conditions. The report highlighted the need to modernize tunnels to support automated vehicles, specifically mentioning optimizations in lighting conditions, accident detection systems, communication infrastructure, and road markings.

However, most tunnels are already equipped with modern **lighting systems** and well-maintained **road markings**. Installing **guidance systems** could further assist autonomous vehicle navigation in tunnels, provided that the markers remain clean and properly maintained for consistent operation. While tunnels are regularly cleaned and refurbished, the absence of vehicle-based standardizations leads to the situation that there are currently no established uniform requirements for optimal lighting conditions, the ideal condition of road markings or special uniform guidance systems necessary for automated driving. In the absence of

standardized guidelines or regulatory frameworks, it is reasonable to anticipate that no further installations or modifications will be made to the existing tunnel equipment.

The KITT research project found that missing GNSS signal currently is the main issue for stopping C-ITS communication. When the GNSS signal is lost, the OBU neither transmits nor receives information. Additionally, the GNSS signal cannot be used for localization purposes inside tunnel structures. The following section discusses several infrastructure-based technologies that are proposed to address the challenge of localization. The main emphasis lies on technologies that require minimal or no modifications to existing and currently installed vehicle equipment.

A cost-effective alternative to GNSS signals are **Bluetooth beacons** installed in tunnel structures [9], [10]. On vehicle side, a special Bluetooth receiving unit is needed. In measuring the received signal strength, the difference in signal time of arrival and its frequency as well as the angle of arrival, precise localization data can be determined. However, the beacons need to be positioned in optimal distances throughout the tunnel. Under ideal conditions, localization precision of 0.5 m to 1 m can be reached. However, due to signal reflection and signal interferences, precise localization may be impaired. Varying temperatures and humidity may additionally alter the correct functioning as well as shorten the lifespan of Bluetooth beacons.

For enhanced precision ranging from approximately 0.1 m to 0.3 m, **Ultra Wideband (UWB) beacons** [11], [12] may be installed at intervals of less than 50 m within the tunnel, given their signal range of up to 50 m. The high accuracy of UWB systems stems from their ability to update positions nearly ten times per second and to utilize higher frequencies as well as greater bandwidths, thereby reducing susceptibility to interference from other communication systems. Nonetheless, UWBs are more expensive than Bluetooth beacons and have limited data transmission rates, restricting their capacity for large data transfers.

Other possible installations on infrastructure side are **GNSS repeaters** [13]. These are currently used in indoor environments where GNSS signals are otherwise unavailable. In order to facilitate this, an external antenna is positioned outside the structure to receive GNSS signals, which are then transmitted via coaxial cable to repeaters installed inside. However, for vehicle localization inside road tunnels, standard repeaters are insufficient: vehicle receivers may incorrectly interpret the location of the installed repeater inside the tunnel as that of the external antenna, thereby compromising position accuracy. Intelligent repeater systems attempt to resolve this issue by generating artificial GNSS signals that mimic real ones. By installing multiple GNSS repeaters throughout a tunnel, continuous GNSS signal coverage can be maintained. Nonetheless, localization accuracy remains lower than in open environments, and both installation and maintenance are costly and require frequent calibration to ensure reliable operation.

Nevertheless, the installation of intelligent GNSS repeater systems would offer two main benefits: enabling localization via GNSS signals and allowing current OBU to exchange information, which makes C-ITS communication feasible.

3. STAKEHOLDER EXPECTATIONS

In the beginning of the project, stakeholder interviews have been conducted and they revealed varying levels of awareness regarding the technical and organizational challenges associated with vehicle localization and communication in tunnel environments. Many stakeholders recognize the difficulties, and some are actively considering potential solutions. Automotive manufacturers generally consider the development of vehicle-side technology for C-ITS largely complete, noting that the next steps must come from the infrastructure side. However, opinions among infrastructure stakeholders are more heterogeneous. While there is consensus that both RSUs and OBUs are essential to enable C2X communication, it is widely acknowledged that GNSS-based OBUs do not function in tunnel environments due to the loss of satellite signal. Although the hardware costs for RSU installation in tunnel structures are considered manageable, stakeholders also point out that a comprehensive rollout is unlikely, given the significant effort required to process and manage the resulting amount of data.

Of particular interest during these discussions was the issue of responsibility. Regarding automated driving in tunnels, stakeholders agree that the responsibility for automated operations should not rest solely with tunnel operators. The anticipated benefits of automated driving include increased safety standards, improved efficiency, and greater system resilience. There is widespread agreement that responsibilities and costs must be clearly allocated: typically, tunnel and infrastructure operators are expected to finance tunnel equipment, while vehicle manufacturers are responsible for outfitting the vehicles. However, binding regulations are needed.

When questioned about operational changes, stakeholders generally see no need for dedicated lanes or tunnel tubes specially for automated vehicles. They stress that safe operation of automated vehicles in tunnels requires precise localization, uninterrupted communication, and robust data security. In order to meet this high safety standards, redundancy across different systems is considered essential. However, there is currently little initiative from the infrastructure side to address communication deficiencies, as there is a lack of standardized regulations and certifications with verifiable performance. Explicit guidelines on interface definitions are lacking, and binding regulations have not been established.

These issues must be resolved to ensure the successful and safe integration of automated and connected vehicle technologies in tunnel infrastructures.

4. OPPORTUNITIES FOR TUNNEL USERS AND OPERATORS

The AUDIT research project offers substantial and multifaceted benefits for a wide range of stakeholders, including tunnel operators, infrastructure owners, vehicle manufacturers, emergency services, and society at large. By enabling automated and connected driving in road tunnels, the project aims to fundamentally **improve traffic quality**. Automated vehicles, supported by advanced C-ITS, can travel with reduced gaps and more consistent speeds, which not only increases the overall capacity of existing road infrastructure but also helps to minimize congestion and bottlenecks. The integration of real-time data exchange between vehicles and infrastructure allows for more dynamic and effective traffic management, resulting in smoother traffic flow, shorter travel times, and a more reliable transportation system.

Furthermore, enhanced reliability and fewer disruptions also **increase the availability and resilience of tunnels**, which is crucial for maintaining the performance of the entire road network, especially on heavily trafficked routes with limited alternatives. For operators, this

means fewer interruptions and potential losses in toll revenue, supporting the financial sustainability of infrastructure management.

In addition, optimized traffic flow not only **reduces travel times** but also **lowers emissions and noise pollution**, contributing to environmental sustainability. The inclusive nature of the technologies developed within AUDIT ensure that people with limited driving abilities can safely navigate through tunnels, supporting broader access to mobility. Overall, the project advances sustainable transportation solutions by integrating cutting-edge vehicle technologies, improving safety, efficiency, and accessibility for all road users.

However, the main focus will be on the impact on **tunnel safety**. Tunnels are critical infrastructure elements with high safety requirements, and human error remains a leading cause of accidents in these environments. Automated vehicles can significantly reduce the risk of accidents by minimizing mistakes related to distraction, excessive speed, or insufficient distance between vehicles, [14]. The project leverages C-ITS to provide additional layers of safety, such as enhanced monitoring, early warnings about hazardous situations like accidents, construction zones, or traffic jams, and precise information for emergency responders. This not only protects tunnel users but also supports rescue operations by delivering accurate details about incident locations and the people or vehicles involved, especially in complex scenarios like tunnel fires.

The safety impacts will be assessed using **systematic risk assessment methods**, considering how automated driving – across SAE Levels 0 to 4 – affects safety in road tunnels. A set of relevant incident scenarios such as breakdowns, collisions, fires or wrong-way drivers, are analysed with both current and future fleet compositions with varying shares of automated vehicles. Safety goals – including traffic safety, but also flow optimization, energy efficiency, emission reduction, cost savings, mobility and inclusion, as well as user comfort – are systematically linked to scenarios and measures. Real-time data streams from connected vehicles are incorporated to enhance risk analysis and support dynamic adaptation of tunnel operations and emergency procedures. The analysis is conducted from both user and operator perspectives – in regular and emergency situations.

5. FEASIBILITY STUDY

At the end of the project feasibility studies will be conducted in real tunnel structures with the objective to perform an experimental validation and evaluation of sensor and localization technologies for automated driving in road tunnels. The aim is to establish the practical feasibility of reliable vehicle positioning and communication under real-world conditions. Representative test tunnels were selected: the Rosenstein tunnel (Stuttgart) in Germany and the Alpine Semmering and Steinhaus tunnels in Austria. A dedicated test vehicle (see Figure 1) is equipped with a diverse array of different sensor types and but also varying sensor quality. This includes multiple LiDAR units, high-resolution cameras, radar, GNSS, IMUs, and C-ITS communication modules.



Figure 1: Test vehicle equipped with various sensors [5]

Measurement runs will be conducted in both directions through the tunnels by forming a closed loop. Particular attention will be focused to the loss of GNSS signals upon tunnel entry and the subsequent performance of alternative localization methods such as LiDAR-IMU fusion and trajectory estimation based on Simultaneous Localization and Mapping (SLAM). The collected data will be rigorously analyzed, including comparisons with ground truth reference models obtained from high-precision laser scans, to quantify positioning accuracy, drift, and the effectiveness of loop closure techniques.

Furthermore, C-ITS measurements will be evaluated for signal quality and reliability, with additional tests planned to investigate V2X-Locate [15] capabilities and the integration of vehicle specific Controlled Area Network / On Board Diagnostic bus data (CAN/OBD2) for enhanced vehicle state awareness. The work plan also encompasses the assessment of sensor artifacts, infrastructure influences, and the operational robustness of communication systems, with iterative refinement based on feedback from consortium partners and technology providers.

The ultimate goal is to derive actionable recommendations for sensor configurations, infrastructure adaptations, and operational protocols that support safe and efficient automated driving in tunnel environments. This includes the development of digital twin models for scenario simulation, the calibration of risk and performance metrics, and the documentation of findings for both scientific dissemination and practical implementation.

6. SUMMARY AND CONCLUSION

Tunnels are central structures in the European road network. They are subject to strict safety requirements, which have been further tightened following major fire incidents. Their importance is growing as the expansion of above-ground transport routes increasingly face resistance. The future transport system will be shaped by connected, intelligent, and automated vehicles that enable cooperative mobility through interaction with infrastructure. Highly automated vehicles (SAE Level 4 and 5) can communicate directly with the traffic management to optimize traffic flow and increase route capacity.

KITT was the first project to investigate how sensor-based and C-ITS-based data can be used for real-time assessment of safety related events in tunnels. Soon it became clear that tunnels interrupt continuous GNSS signal coverage. The lack of precise positioning leads to pausing

of communication modules in C-ITS-enabled vehicles, resulting in no further messages being sent. The challenges of positioning and communication in tunnels have so far been scarcely examined and require further innovative approaches.

The AUDIT project represents a pioneering effort in advancing automated and connected driving within road tunnels, a domain that poses distinct technical and safety challenges. AUDIT places strong emphasis on the functionality of vehicle-based sensors in tunnel structures as well as on C-ITS, which facilitates real-time data exchange between vehicles and infrastructure. AUDIT also explores advanced wireless positioning techniques to overcome the limitations of GNSS signals in tunnels, taking into account the complex radio channel characteristics caused by reflections and signal fading. While simulated GNSS systems are available, their impact on C-ITS communication in tunnels remains largely untested in the DACH region.

Looking into the future, the insights and technologies generated by AUDIT will play a crucial role in enhancing safety and operational efficiency in tunnels and other critical infrastructure. The project's outcomes are expected to pave the way for more resilient, intelligent, and sustainable mobility solutions, fostering the development of unified standards and best practices for automated driving in complex environments. As automated and connected vehicles become increasingly prevalent, the work initiated by AUDIT will help ensure that tunnels are not only safe but also fully integrated into the future of intelligent transportation systems.

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