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Usage of V2X Applications in Road Tunnels

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Featured Application: This article provides a general overview of technological aspects and limitations of tunnels with respect to smart technologies such as C-ITS.

Abstract: Many smart city applications work with calculated position and time using the Global Navigation Satellite System (GNSS) signals for enhanced precision. However, there are many places where the availability of GNSS is limited, e.g., road tunnels, which are an essential part of transport infrastructure. Tunnels also require greater attention and greater importance of approaches to ensure the safety and security aspects of traffic. The safety, distribution of information, awareness, and smooth traffic can also be ensured by V2X applications, but the current position is also needed. An experimental analysis of data connection and communication availability was performed in the Blanka tunnel (Prague) and its surroundings. The main objective of the work was to find and clearly describe the tunnel blind spots, with an emphasis on communication between cars and potentially between cars and infrastructure. This article summarizes the evaluation results of the V2X tunnel experimental test, the outputs from the analysis of these blind spots, and it provides a future perspective and suggestions that make tunnels smart by using advanced positioning approaches.

Keywords: C2X; C-ITS; connectivity; dead reckoning; GNNS; positioning; safety; smart city; stationary vehicle; tunnel; VANET; V2X

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1. Introduction

Today, the importance of city management is focused on new technologies, sustainability, social aspects, and complex solutions. It is based on the realization of new cases, architecture improvements, IoT deployment, data connectivity, and integration of these particularities, m main objective of ensuring acceleration, the knowledge-based approach, future strategies, and sustainable evolution of livable cities [1–3]. The importance of livability also lies in the movement, accessibility, social, and environmental aspects that fall within the scope of urban transportation [4]. The hidden but essential parts of the transport infrastructure are the tunnels that ensure smooth traffic and connections between the city districts. Tunnels seem to be the perfect way to achieve the criteria for a smart city mentioned above, but several drawbacks are associated with them, especially from a technological point of view. This hidden part of the infrastructure does not allow common positioning systems [5], their applications, and sometimes data connectivity, and thus the tunnels are smart and also ineffective for many applications at the same time.

In the context of the article, the meaning of infrastructure is related to the tunnel itself (construction), control systems, equipment, and devices implemented in the tunnel, as well as in the surroundings, such as traffic light controllers, variable message signs, informative panels, etc., which are implemented on the access ramps to the tunnel and the tunnel exits.

Tunnels are an essential part of urban engineering and smart city ecosystems. First, due to the impact on traffic in the city [6], and second, due to the wide range of installed equipment that provides the possibility of data acquisition, to regulate the maximum allowed speed or entrance into the tunnel, and thus indirectly the number of vehicles in the city districts [7]. The implementation of the tunnel complex in cities brings many benefits, but the financial aspect of investing in construction and then even more in operation and maintenance is not negligible [8–10].

One of the major problems concerning tunnels is the Global Navigation Satellite System (GNSS) availability [11]. Since the tunnel is "hidden", many applications are limited due to positioning requirements. Some of them only notify the user that the GNSS signal is lost, while other ones are based on statistical methods, computation, usage of external devices for supplementary measurements, communication, etc. [12,13]. The problem of a lack of GNSS signal availability has been occurring in tunnels for many years. Whereas smart technologies, navigation systems, and other applications are growing in popularity together with the trends of smart, resilient, and sustainable cities, the problem with GNSS is also growing and its importance is increasing. For this reason, the problem becomes the issue of how to solve positioning (not only) in tunnels.

For the mentioned reasons, it is necessary to take into account these blind spots in smart mobility and transportation solutions. Tunneling and tunnel equipment should be one of the main disciplines in urban planning and engineering. It is important to provide a solution for all road users, including road users in tunnels, where, for example, navigation is crucial, and its functionality may have implications on traffic throughout the city. However, the most important to ensure are the safety applications, e.g., smooth passing of an emergency vehicle, dissemination of warning information, as well as about the failure in tunnels or tunnel closure. Vehicular communication (V2X—vehicle-to-everything) is one of them [14,15], but it does not work properly in locations where GNSS is not available, and thus the analysis of V2X communication in the tunnel is presented in the article with a focus on assisted positioning methods due to V2X communication requirements in position accuracy and its continuous updating during the data transmission.

Within the research, it was found that the positioning of vehicles in vehicular ad hoc networks (VANETs) is crucial, as well as for the purposes of communication between cars and infrastructure. In normal operation of C-ITS (Cooperative–Intelligent Transport Systems), GNSS-based localization is mainly used. However, in tunnels, the GNSS is limited or unavailable. The proposed research strategies are presented in several articles, for example, New Roadside Units (RSU) Positioning [16] by Malik, which presents a specific positioning approach that could be used for vehicular communication. However, there are no specifics mentioned for tunnels, and in addition, the RSU also requires GNSS as well as on-board units placed in the cars. Similar work [17] is presented by Fouda et al., where the tunnels are considered. The simulated numerical results show the possible improvements for V2X communication. In Wang's article [18], the RFID-assisted approach is presented, and then the Matlab simulation is established. In Hashmi's article [19], the fusion model of GPS (Global Positioning System) and non-GPS systems is presented with an emphasis on VANETs. However, the results only show the output of the simulation tool.

For this reason, the experimental analysis of V2X communication based on assisted localization methods was performed under real conditions and is presented in the article. The main goal of the experiment is to verify whether V2X communication could be possible under the conditions using assisted localization methods in the limited GNSS availability environment, for example, in the road tunnel, where V2X communication is very important, especially from a safety point of view. The unique experimental test was carried out in the Blanka tunnel complex in Prague, because the tunnel is long enough to completely lose the GNSS signal (more than 5 km, which is vertically and horizontally divided and contains several intersections directly in the tunnel) and the verification of the C-ITS communication could be applied there. Within the test, the validity of C-ITS messages was constantly verified using the unique V2X software stack adopted in the testing units, so the invalid messages are ignored according to the ETSI standards, e.g., because of the positioning accuracy, and thus the V2X messages are not displayed in the application.

The uniqueness of the whole experiment lies in the fact that the tunnel was closed, which also enabled the testing of standardized scenarios of V2X communication directly in the tunnel, for example, a stationary vehicle use case in the tunnel, which would not be possible during normal operation with real traffic. Experience and needs with tunnel technology in Prague were also taken into account in the most common use cases related to tunnel emergencies. The most common case of extraordinary events is the stationary vehicle (failure, accident, etc.) that evokes the closure of a tunnel or a lane in the tunnel. Another common phenomenon is the emergency vehicles of the police, fire brigade, ambulance, or the intervention of a service vehicle in the tunnel, which also leads to the closure, or restriction of traffic in the tunnel at least. Due to the length of the Blanka tunnel and the junctions inside, the case of a stationary vehicle is the appropriate one for using the precise location, which fails via GNSS-based positioning, that is commonly used in the field of C-ITS and other smart applications. Therefore, the unique C-ITS testing was performed in the tunnel, where positioning was ensured by assisted localization approaches based on Dead Reckoning. The test results may benefit the subsequent operation of C-ITS in places where GNSS availability is limited. Therefore, the pilot test and its methodology were designed with a focus on the verification of whether the C-ITS is applicable and usable in the tunnel, and if so, further testing could be performed in a real traffic scenario with normal traffic flow.

The remainder of the article presents background information that provides general information on positioning methods for enhanced precision together with requirements on V2X communication. Then, the methodology of the experiment is presented by a description of testing conditions, testing scenarios, and data acquisition with the evaluation procedure. It continues with the results of the experimental analysis. All the results and context are then further discussed, and the future work is presented.

2. Background

2.1. Positioning Approaches

Over the years, several approaches have been developed and applied with the main goal of ensuring additional data for the estimation of an accurate position based on video processing [20], sensor data acquisition [21], 3D accelerometers [22], gyroscope and odometry [23,24], beaconing [25], and other communication methods, such as wi-fi signal strength and fingerprinting [26], etc.

Moreover, various methods, such as Kalman filtering [27], Dead Reckoning [28], Map matching [29], and others, have been devised. These methods enable computation and filtering of input data and provide position refinement. Each of them has a specific value and benefit for certain purposes and usages, and each method calculates the position with an error.

The results of the experimental measurements are mentioned in [30], where the evaluation of GPS, Kalman filtering, and Dead Reckoning is performed and compared to the ground truth reference.

Each of the methods, including GNSS, respectively GPS, show an error. This implies that their combination could be a way to obtain a better accuracy estimation, especially when using Map matching, which is based on the map layout and reference positions in the map. These methods are relevant and are used in mobility solutions and applications, where the position of the vehicle could be calculated and pinned on the map [27–30]. This can also work in the tunnel, where the path is clearly defined.

Lastly, in the following figure (Figure 1), a schematic layout of the Dead Reckoning method and its functioning is presented. This functional schema was selected because it directly shows the use case for positioning in the tunnel and also because the Dead Reckoning approach was used within the experimental analysis presented in the article.

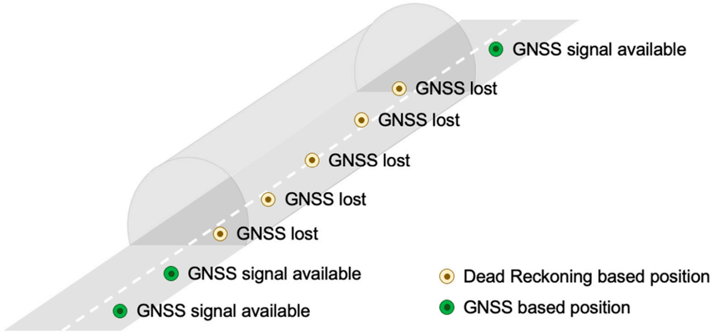

Figure 1. Utilization of Dead Reckoning.

2.2. V2X Requirements

Determining the position of the vehicle, mobile phone, advanced units, and technologies is crucial, especially in traffic and smart mobility solutions. In the field of C-ITS and VANETs, where vehicles should communicate with each other, position accuracy is essential. It is necessary to know where the vehicle is located and to whom it will send information. In the basic principles that are stated, recommended, and standardized for the European region by ETSI (European Telecommunications Standards Institute), for vehicular communication, the accuracy of the position can vary, but in some new cases, such as Platooning (see Figure 2), the information about the time and position is required at intervals of at least 20 times per second [31]. This is practically impossible to achieve on the basis of the received GNSS signal in the tunnel, where no satellites are visible [32].

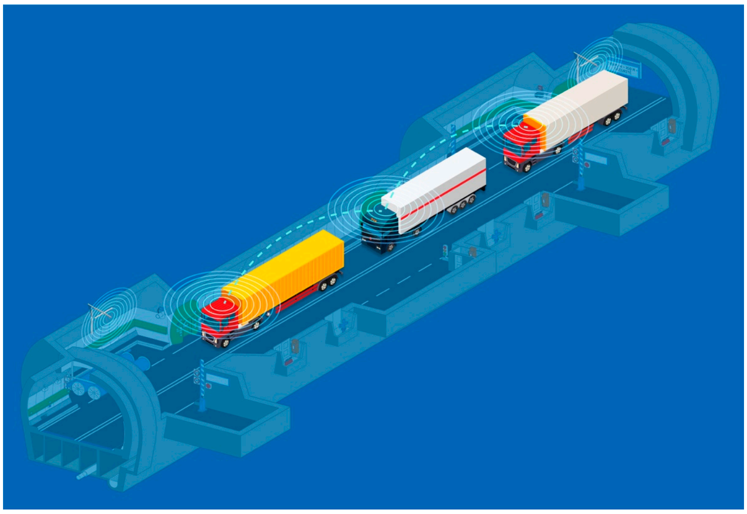

Figure 2. V2X Platooning [33].

The facts, prerequisites, experiences, and suggestions mentioned above led to the idea to test V2X communication in the tunnel and its surroundings. This was primarily to enhance knowledge about the usage of V2X applications with limited GNSS signal availability, such as tunnels, by practical experiment and measurement, to test further operating characteristics in the tunnel environment in parallel, but most of all, to obtain an answer on how the tunnel is prepared for the upcoming challenges of smart cities.

3. Methodology

For V2X communication testing, a wide range of methods can be applied. Some of the methods involve a technical approach [34], and some directly relate to specific use cases, such as communication with traffic lights [35], etc. There are many cases related to testing of communication among vehicles, but also to infrastructure equipment, pedestrians, cyclists, etc. Some of the cases also respond to the development of autonomous vehicles and their role in transportation [36,37]. Various devices can be used, such as tools for the assessment of validity [38], compliance with standards [39,40], or security aspects [41]. For the purposes of the experimental analysis, the functional test in the field was performed including communication logging for further subsequent technical post-analysis.

3.1. Test Conditions

Within the Blanka tunnel test, hybrid OBUs (on-board units) were used. These units support local communication over the ITS-G5 (European standard for vehicular communication operating at 5.9 GHz) and cellular communication over the LTE (Long-Term Evolution) networks. Each of them was installed in the vehicles that were part of the experiment. In Figure 3, photos of the installed equipment are presented. Both units were set with properties that allowed the use of the Dead Reckoning method based on data from the 3D accelerometer and the Map Matching when the V2X use case [36] was generated. This has become a basic prerequisite for the test scenario of whether V2X communication occurs without GNSS signal reception.

Figure 3. Hybrid C-ITS OBU Smart GEAR used during the test.

The V2X communication assessment in the tunnel must be carried out under specific safety precautions. Due to this fact, it was feasible to perform the test only at the time of tunnel closure, which, on the other hand, made it possible, for example, to test scenarios such as a stationary vehicle in the tunnel and beyond.

3.2. Testing Scenarios

The test was carried out in two main phases. First (pre-test), the equipped vehicle went through the tunnel to check if the OBU was working properly while the GNSS signal was lost. In the second phase, the major test was performed and communication between both vehicles was tested and verified.

3.2.1. Pre-Test

The first part of the testing was performed under real traffic conditions. The vehicle was equipped with an OBU and went through the whole tunnel. The main assumption was that the unit moving in the tunnel would correctly estimate its position while GNSS was not available. This first case was necessary to prove for further testing and to verify that the measurements were valid for the second phase. During the test, the incoming communication over the LTE network was also analyzed (from the backend), which should provide confirmation that the LTE is available in the entire Blanka tunnel, as defined in [42], or not. A schematic layout is shown in Figure 4.

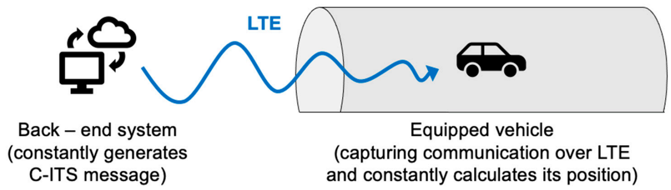

Figure 4. Schema of the pre-test.

3.2.2. Test of V2X Communication

In the second case, communication between vehicles was tested. One vehicle was inside the tunnel and stopped to simulate the stationary vehicle. The vehicle was placed in the first section of the tunnel (500 m from the entrance, 600 m before the first exit), because this part was dedicated to testing during the closure. The stationary vehicle was continuously generating the V2X use case, so during the entire test, standardized C-ITS messages of type DENM (Decentralized Environmental Notification Message) [43] containing its position, event position, traces leading to the event, etc., were broadcasted to the surroundings, and the backend system as well, while the second vehicle arrived after a few minutes in the tunnel and along the way it was receiving messages from the surroundings and the backend. A basic scenario schema is shown in Figure 5.

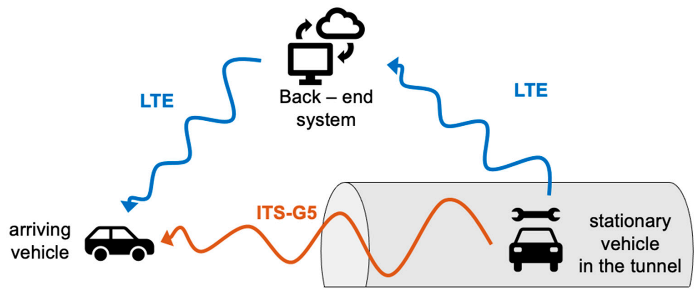

Figure 5. Schema of the major test scenario.

One of the research questions within the experiment was also whether it was possible to deliver the C-ITS message over the ITS-G5 communication network outside the tunnel. If so, how far is it possible? It was also important to compare both approaches to communication and find differences. The next question was related to the validity of the message with respect to the GNSS supplement by calculating the time and position using the OBU algorithm.

3.3. Methodology of the Data Acquisition and Evaluation Procedure

During the test, both OBUs logged incoming and outgoing communication. It was logged in the PCAP (Packet Capture) file format, which is commonly used in telecommunications. Therefore, it was possible to check in real time whether these vehicles are connected or not.

Furthermore, when the received C-ITS message was valid, the information was expressed in a mobile app that was used for the purposes of the test as a Human–Machine Interface (HMI). It should be noted that the validity of the C-ITS message is based on many parameters, and it does not matter whether the receiving OBU has the correct time and position. The message may be invalid even in this case, for example, because the traces leading to the C-ITS event are incorrectly defined.

Although the mobile app was only used in real time and no data are available after the test, the data captured from the OBUs have been prepared for further post-process analysis. These data have been essential in the test evaluation procedure. Each of the C-ITS messages contains several parameters, but for the analysis, the timestamp and the position (latitude, longitude) were the main ones.

From these C-ITS data, a filtration was applied to obtain the position of the vehicle at the time the C-ITS message was received from the stationary vehicle. It allowed for the calculation of the difference between the positions of the stationary vehicle and the arriving vehicle, and thus the communication range was known.

Another approach within the test evaluation was a map projection of the positions of the arriving vehicle during the entire test. It provides an opportunity to check whether the positions were correct in terms of matching with the layout of the map, but also provides a general overview, where it is possible to receive and obtain C-ITS information concerning the position of the source that generates C-ITS messages.

4. Results

Analysis of V2X communication in the tunnel environment showed several outputs and results. Firstly, LTE connectivity had been available throughout the test, regardless of whether the equipped vehicle was placed in the tunnel or outside. The LTE coverage was sufficient, and the C-ITS messages from the backend were captured throughout the Blanka tunnel. However, the visualization of results was influenced by the positioning error, which occurred after 3 km from the tunnel entrance (see Figure 6). The testing direction was from southwest to northeast.

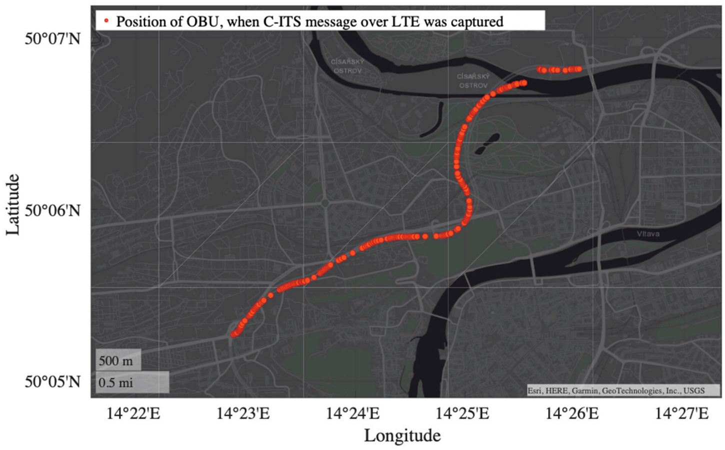

Figure 6. Captured C-ITS messages from the backend over LTE.

The pre-test showed that the positioning error was growing with the length of the testing range. However, the position in front of the tunnel was relatively correct, and thus the major test could be performed.

During the major test, it turned out that the OBUs were communicating with each other. The OBUs correctly (at least sufficiently for the V2X commutation) computed their own position even though the GNSS signal was not available. It was also possible to observe on the HMI that the C-ITS messages were valid, and that the information was displayed on the mobile app when the arriving vehicle was closer to the stationary vehicle. This means that both OBUs calculated the time and position in the same way. The testing showed that the OBUs are prepared for unexpected circumstances also in the tunnel, and it is possible to disseminate information, for example, about the stationary vehicle in the tunnel. A visualization of the information is shown in Figure 7, and the mobile app also provided a relatively correct estimate of the distance between vehicles.

However, the output showed that the position and time updates were limited. During the test, the display of information was not continuous, and the information about the distance changed in unexpected steps compared to the knowledge of the proper system working under standard environmental conditions. Sometimes, the information on the

HMI disappeared for a while, which probably means that the position was inaccurate (unavailable) at that moment.

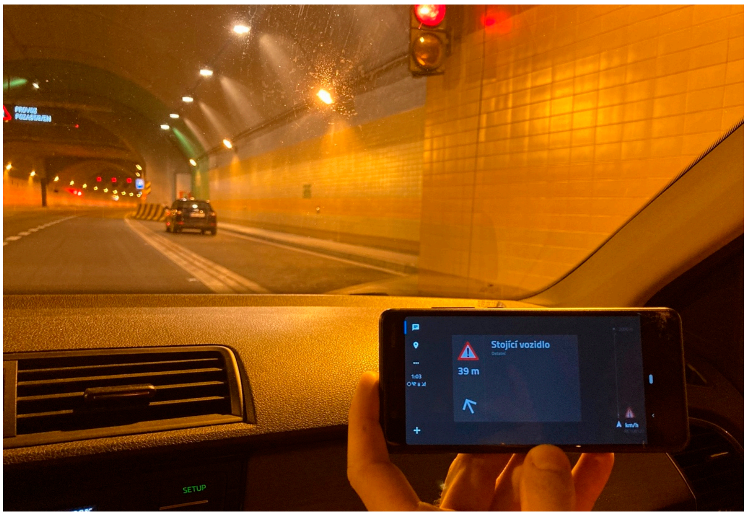

Figure 7. Testing of the V2X scenario (stationary vehicle) in the Blanka tunnel.

Based on the processed data from the C-ITS communication, it is quite clear that the communication over ITS-G5 was limited. However, the results showed that line of sight is not necessary for communication and that the signal from the transmitter sufficiently bounced off the tunnel walls. On the other hand, the signal was receivable only in the closer surroundings before the tunnel entrance. From the data log, it follows that the communication range was hundreds of meters (see Figure 8). It is necessary to keep in mind that each tunnel is specific and different, so the conditions of V2X communication may also be completely different. Quite a positive result was also found for packet delivery, where it was possible to observe that a similar number of messages were captured over ITS-G5 as over LTE.

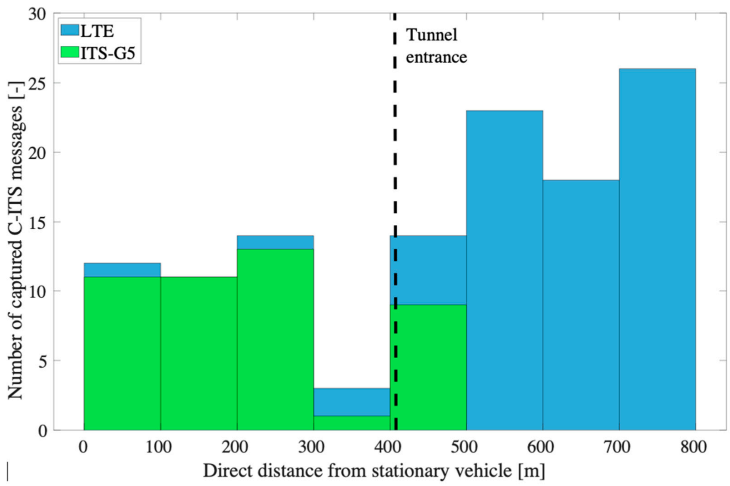

Figure 8. Captured C-ITS messages in terms of distance from the stationary vehicle.

From Figure 8, it can be seen that a lack of communication occurred while the arriving vehicle was entering the tunnel tube. This is probably due to the recovery of the system after the unavailability of GNSS. This could be a crucial part of communication, because the arriving vehicle could not know when the GNSS was exactly lost and when the procedure of positioning based on the 3D accelerator should be applied.

However, the vehicles were connected when the direct distance was not guaranteed, probably due to signal reflections on the tunnel wall. The fact that the tunnel was empty, without vehicles that would normally be passing, should also be taken into account, because the conditions during the test were specific.

In Figure 9, the position of the arriving vehicle (when the C-ITS message was received) is shown on the map, as well as the position of the stationary vehicle. It is possible to observe that the update of the position corresponded to the layout of the map and that the position was located on the road. It is also possible to see that the first message received from the stationary vehicle was exactly at the entrance to the tunnel.

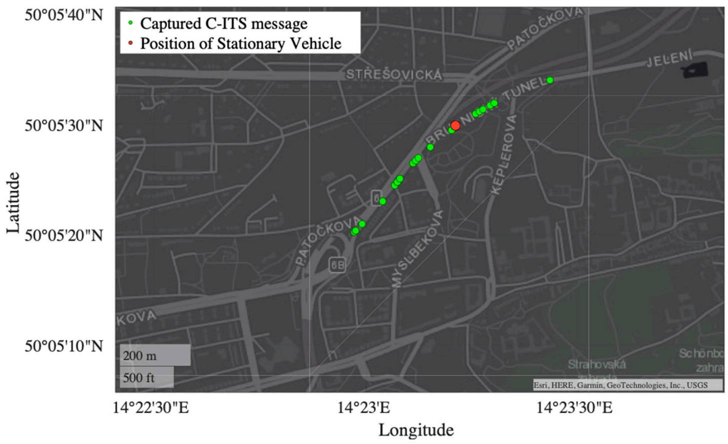

Figure 9. Captured V2X communication over ITS-G5.

Compared to ITS-G5 communication, V2X communication over the LTE network (see Figure 10) has great benefits, such as the availability of information about the stationary vehicle in the tunnel and its delivery with considerable advanced notice. From the driver's perspective, it is possible to react to the situation, and it is also possible to change the path or stop the vehicle in a case where the tunnel should be evacuated, for example, due to a traffic accident.

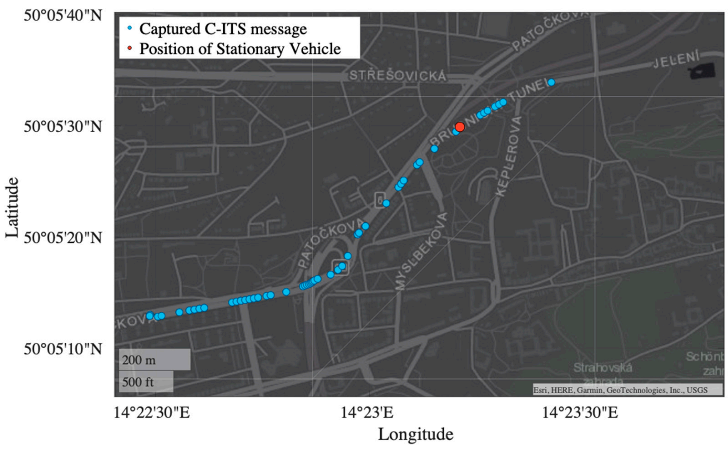

Figure 10. Captured V2X communication over the LTE network.

It may seem that the reception of C-ITS messages outside the tunnel was more frequent compared to the reception when the vehicle arrived in the tunnel. Unfortunately, this is caused by the position update. The frequency of the received packets was almost the same throughout the test, but the visualization on the map did not take into account the number of messages captured in the same position. This fact slightly distorts the result, but at the same time, it points out that the position updating could be problematic.

5. Discussion

From the research, but also from the testing and analysis, the results indicate that a loss of V2X communication may occur in the tunnels. Tunnels are equipped with a wide range of technologies and devices, but the availability of GNSS is still not sufficient. There are many approaches on how to supplement it, such as an example with the tested scenario. The problem with these complementary solutions and techniques consists of the fact that the position and time accuracy vary and are not centralized, unlike with the solutions based on the GNSS signals.

It may occur that each application will work in a different way, and will compute the position and time with a lack of accuracy compared to the others. Each application will work within the particular solution but with a unique error, and thus each vehicle could compute different latitude and longitude while both are at the same place.

In the case of V2X communication, it does not work properly when vehicle positions are decentralized, especially in use cases where the position and time validity of the event are crucial. This is specifically related to "moving" events, such as slow vehicles, maintenance, and service spreader vehicles on roads, but even more so in use cases such as approaching emergency vehicles, emergency electronic brake light, platooning, etc., where the validity of time is very short, and the position must be precise.

The result of the evaluation also showed that communication over the cellular network might be more efficient with regard to the dissemination of the provided information. Especially in the case of V2X communication in the tunnel and its surroundings, where the possibility to change the path, or stop the vehicle, etc., is not possible, the cellular approach could be more efficient, and it could provide information in larger areas. It is also presumable that local microwave V2X communication over ITS-G5 will be worse in normal traffic flow in the tunnel due to the space being filled by other cars.

Using hybrid communication, it is possible to share the data and integrate them into the tunnel control system, as well as the city traffic control management system [44], and thus it is possible to plan, schedule, and control these systems as a project with defined processes regarding risk management and decision-making solutions [45].

As part of the design and use of C-ITS in the tunnel, it is possible to implement other future plans and recommendations for tunnel construction and its development. In the tunnel, the data transmission and distribution of information could be carried out directly to the vehicle about the status of the tunnel itself, and about the particular parts such as variable message signs, speed limit, etc., but the tunnel could also obtain information from the vehicle. Examples of data and information from the vehicle and the tunnel infrastructure are as follows:

- Travel time in the monitored section
- Average speed (section speed)
- Travel time delay in the monitored section
- Detection of a traffic jam in the monitored section
- Detection of a braking/stopped vehicle and direction of vehicle movement
- Vehicle acceleration/deceleration
- Use of vehicle control units
- Number of people in the vehicle (for evacuation modeling)
- In-vehicle infrastructure information (speed limits, delay information)
- Approaching emergency vehicle position in the tunnel
- Position of accident, stationary vehicle, or cargo
- Information about hazardous event/position in tunnels, evacuation information, etc.
- Information for drivers in convoys, information about approaching IRS vehicles
- Vehicle maintenance position to prevent potential collisions and emergency lane closures

This article focused not only on C-ITS communication between vehicles using LTE and ITS-G5, but also in connection with the functions of complex tunnel infrastructure, which is very large. The construction of tunnels includes several junctions, large elevation gain, but also the fragmentation in the vertical arrangement (road bends), and thus the vehicle's own signal propagation is also limited, and it also creates an increased potential of accidents, emergencies, and extraordinary events in the tunnel. This could negatively affect the operation of the tunnel itself, and the impact on the safety and fluidity of traffic should be taken into account as well. The C-ITS can be seen as an appropriate technology to help with the safety management and has real benefits for the future autonomous operation of smart cities, and also for tunnels. Therefore, it is appropriate to examine the possibilities of using the C-ITS in more difficult and demanding conditions in more complex structures and environments, not only on the surface, but also below the surface, i.e., in tunnels.

6. Future Work

Positioning improvements are needed and should be considered in future V2X communication strategies, as well as urban planning and city management, because the availability of GNSS positioning is limited. However, for many applications, the GNSS approach is only one working solution. In some cases, an assisted approach could be used, e.g., for navigation, route planning, etc. However, in V2X communication, the centralized positioning approach is required at the level of the entire tunnel. The centralized approach is needed for the synchronization of all units placed in the tunnel at that moment.

A progressive approach is the use of BLE-based communication [46] as a complement to C-ITS, which can very accurately detect indoor positions [47], for example, vehicles in the tunnel, by transmitting accurate information to the navigation and tunnel control system with the minimization of cost investments. The application is planned for future work and further development, and its usage for the V2X application will be considered in the subsequent experimental studies.

Positioning for the purposes of V2X communication in the tunnel could be based on the specific approach of the roadside unit (RSU) positioning [16,17], which could be implemented in the tunnel, and not only in positioning, but also in transmission of V2X data and its dissemination throughout the tunnel. Further applications could also be applied, and the RSUs could be connected to the tunnel control system and devices in the tunnels, such as variable message signs, etc. This approach could be a systematic way of how to use assisted localization methods with limited GNSS availability. The main advantage is the possibility of implementing further functionalities, such as time corrections. Furthermore, the security aspects of advanced approaches should be prepared, especially for the operation of autonomous vehicles, where security is crucial [48–50].

It is also necessary to perform advanced analysis on more data, in all parts of the tunnel, but also in different tunnels to ensure that the solution could be applied everywhere. It is absolutely essential to prove the same with other V2X units.

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Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

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Conflicts of Interest: The authors declare no conflict of interest.

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