Evaluation Study of Inertial Positioning in Road Tunnels for Cooperative ITS Applications

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***Abstract*—Global Navigation Satellite Systems (GNSS) are unreliable positioning sources in road tunnels, as the satellite signals are unable to reach deep inside the tunnels. As innovative technologies emerge within the transportation sector – e.g., with Autonomous Vehicles (AVs) and Cooperative Intelligent Transport Systems (C-ITS), higher availability, timeliness and accuracy of positioning services is demanded. In GNSS-denied environments such as road tunnels, Inertial Navigation Systems (INS) can leverage the use of accelerometers and gyroscopes to estimate the vehicle's position while the GNSS positioning signal is lost. However, these systems have proven to be unreliable in long tunnels, as noise artifacts in inertial sensors introduce errors which accumulate over time. This paper aims to investigate the impact of these on the positioning accuracy in road tunnels, through modeling a commercially available Inertial Measurement Unit (IMU) and simulating driving routes through various road tunnels within Norway, a country with a complex terrain and many road tunnels. Through these measurements, we also investigate if the positioning requirements of modern C-ITS applications are met in various tunnels, depending on the tunnel length and curvature. Finally, this work lays the foundation for developing a framework for designing cost-effective and reliable indoor positioning solutions for road tunnel environments.**

***Index Terms*—positioning, road tunnel, inertial navigation systems, cooperative intelligent transport systems**

I. INTRODUCTION

Road tunnels are essential elements of public road systems. In regions with highly mountainous terrain and large bodies of water separating communities (e.g., in Norway or Switzerland), tunnels allow for reducing travel times significantly. In urban areas, tunnels can also help alleviate congestion, reducing pollution and allowing to pedestrianize the streets [1]. At the same time, maximum safety in road tunnels is critical for the public notion of safety due to the hazards of fire and explosions for road users in enclosed environments. Even though road accidents are less likely to happen in tunnels than in open air, they can be significantly more hazardous [2]. As a result, strategies for incident prevention, detection and response need to be tailored to road tunnel scenarios.

With the latest developments in autonomous driving and Vehicle-to-Everything (V2X) communications, future roads will be inhabited by Connected and Autonomous Vehicles (CAVs). Benefited by the recent advances in sensor, artificial intelligence and communication technologies, traffic efficiency and safety applications are being developed within the Cooperative Intelligent Transport Systems (C-ITS). While newly emerging C-ITS applications and use-cases are being widely tested and validated in initiatives such as C-ROADS [3], little focus has been made on the road tunnel scenarios. While there are high potentials in using C-ITS for delivering tunnel safety services [4], [5], there remains several challenges related to the operation of CAVs in road tunnel environments that need to be addressed; and vehicle positioning remains a major one.

While more complex and longer tunnels are being designed and constructed (e.g., 27 km long sub-sea Rogfast tunnel in Norway [6]), positioning accuracy requirements to support future C-ITS safety services grow. Hence, the need to provide high reliability in-tunnel positioning service arises.

Most navigation applications can tolerate a few meters of positioning error, however, advanced C-ITS applications where vehicles must transmit their real-time location several times per second (e.g., vehicle platooning) have more strict accuracy requirements. As part of the Key Performance Indicators (KPI) for future C-ITS applications, positioning accuracy requirements have been proposed by partnerships such as the 5G Infrastructure Public Private Partnership (5G-PPP) [7] and the 5G Automotive Association (5GAA) [8]. The European Commission has also published the European Radio Navigation Plan (ENRP) [9], which defines timing and accuracy requirements for air, maritime and land transport. We have collected some of these requirements in Table I.

Road tunnels often lack GNSS service coverage, as satellite signals are mostly unable to penetrate deep into underground facilities. Although a subset of *short* tunnels may have limited GNSS coverage albeit with limited accuracy, long tunnels are fully GNSS-denied, which prevents such tunnels from benefiting from advanced GNSS precision enhancement methods such as Real Time Kinematics (RTK) [10] and Precise Point Positioning (PPP) [11].

Several solutions have been proposed for reliable position-

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ing in road tunnels using various wireless technologies – e.g., using Wi-Fi [12], Bluetooth Low Energy (BLE) [13], RFID tags [14], V2X [15], [16] or cellular networks [17]. However, these solutions often require the deployment of radio beacons, base stations or Road Side Units (RSUs) within the tunnel, which depending on the deployed solution may influence the investment on the tunnel and its maintenance costs, and as a result impact the cost-effectiveness of the project [18]. This is especially noteworthy for long tunnels which could require hundreds or thousands of beacons.

On the other hand, Inertial Navigation Systems (INS) – also known as Dead Reckoning (DR) algorithms – use in-vehicle Inertial Measurement Units (IMUs) which can integrate accelerometers, gyroscopes and magnetometers. These systems use acceleration, angular speed and magnetic field readings from sensors to predict the vehicle's trajectory given an initial state [19]. While these systems do not require any hardware deployment outside the vehicle and they can operate regardless of the environment, they are also known to be highly sensitive and inaccurate over time due to the noise in the electronic circuits [20], which in turn introduces the need for calibration measures. As a results, INS are often seen integrated together with other systems to increase the service reliability, with the use of Kalman fusion filtering [21].

Few earlier works have investigated the challenge of positioning inside the road tunnels. While some tunnels may have simple layouts with low curvature and few to no intersections, they can also be long in the order of kilometers, that leads to unavoidable positioning drifts. An earlier investigation performed by Aventi AS has reported significant deviations in the vehicle positioning when driving through Bjørnegård tunnel (1.9 km long) in Oslo [22]. A comparable field trial was performed in the Blanka tunnel (5.5 km long) in Prague, reporting increasing positioning error as the vehicle enters deep inside the tunnel [23]. However, despite these preliminary field trial investigations, a thorough and systematic investigation of INS performance supported by numerical models in a variety of road tunnels is still missing in literature.

As a result, this paper aims to fill this research gap by exploring the INS performance in different types of road tunnels via simulations, using Norway as a reference, which forms a good use-case scenario due to its complex terrain and high density and variety of road tunnels. Thus, this work contributes to the state-of-the-art in the following ways:

1. characterizing INS accuracy in all road tunnels in Norway, including $\sim$1500 tunnel sections with various profiles based on realistic data;
2. exploring the readiness level of road tunnels in Norway for various C-ITS applications in terms of positioning accuracy;
3. evaluating the impact of tunnel length and curvature on the positioning accuracy;
4. and offering a framework for designing cost-effective positioning solutions for future tunnels.

The remainder of this paper is structured as follows: Section II discusses the related work to the use of INS for positioning; Section III lays out in details the methodology used in this paper's simulations; Section IV presents and discusses our simulation results; and finally Section V concludes the paper.

C-ITS Application	**Positioning Accuracy**
Road Navigation	< 10 m [9]
Emergency Response	< 4 m [9]
Emergency Break Warning	< 1.5 m [8]
Automated Overtake	< 30 cm [7]
High Density Platooning	< 30 cm [7]
Collision Avoidance	< 10 cm [9]

TABLE I: Positioning requirements for some C-ITS applications, collected from [7]–[9]

II. RELATED WORKS

The idea of inertial navigation is not new as the first scientific works proposing the use of inertial sensors for navigation date back to 1970s to trace the position of aerial objects. However, it has received renewed attention in recent years [19] due to the advances made in sensor technologies, electronics, signal processing techniques, and machine learning, which leverages the use small integrated devices with high computational power of modern processors [24]. A survey of the progress made within the field of inertial sensing has been provided by [25].

While INS are usually integrated together with GNSS, navigation systems must account for the GNSS degradation or outage that can happen as the vehicles move through different environments. There have been several experimental studies evaluating the accuracy of integrated INS/GNSS in public roads; for instance, authors of [26] evaluated the performance of such systems in railway vehicles using several commercial solutions and measured the impact of GNSS outage on the positioning error. Other studies have proposed more advanced inertial navigation algorithms to perform under degraded or GNSS-denied environments [27]. The work in [28] uses a trained machine learning model with realistic IMU data to generate better error models which can help reduce positioning drift. A similar approach has been taken by [29] using convolutional neural networks.

Since many modern vehicles have integrated camera systems, some works have investigated the integration of INS with computer vision techniques to further improve the attitude estimation in GNSS-denied environments [30], [31]. Authors in [30] evaluate the use of a binocular camera to measure lane width together with inertial sensors and odometer data in order to estimate the lateral position of a vehicle on the road. The work in [31] proposes the use of vehicle cameras to detect kilometer signs on the road to correct the accumulated positioning error of an INS/odometer system. Other works have proposed similar integration using LIDAR data instead of computer vision [32].

Another set of studies explore the use of radio communications for positioning. In [16] a method is proposed that fuses inertial positioning with 5G-V2X-based ranging, which uses the time and angle of arrival of the signals emitted from a RSU, achieving sub-meter accuracy. The study in [15]

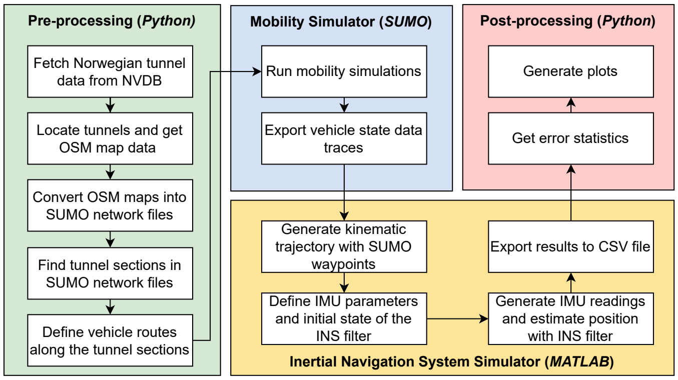

Fig. 1: Overview of the methodology used in this work.

proposes a cooperative positioning system in which nearby vehicles share their IMU readings and position estimations through V2V communications to help each other improve the positioning accuracy. Similarly, authors in [33] propose the use of visible light communications through LEDs located on fixed tunnel infrastructure, which vehicles can use to locate themselves.

Another taken approach is the use of Map Matching (MM) along with IMU data. Since vehicles move through public roads that are documented in public databases, noisy INS estimations can be *aligned* with map data to improve the positioning accuracy [34]. The authors in [35] proposed and evaluated a framework that uses inertial readings to detect road semantics – e.g., speed bumps, roundabouts, junctions – which can be matched with map data to correct INS drifts.

While there have been significant efforts to improve INS in the absence of GNSS, a detailed investigation of their performance in road tunnel environment is absent. Addressing this issue is the main goal of this paper.

III. METHODOLOGY

The experimental methodology in this work is summarized in Figure 1. First, reliable data on the Norwegian tunnel systems is obtained from the NVDB RESTful API [36] provided by the Norwegian Public Roads Administration (NVDB). To simulate vehicle mobility through these tunnels we use the open-source SUMO mobility simulator [37], which allows to generate custom mobility scenarios using real map data from Open Street Maps (OSM). Then, the inertial positioning is simulated by feeding vehicle trace data into MATLAB's inertial navigation package [38], which include detailed models of accelerometers, gyroscopes and sensor fusion filters.

A. Tunnel data

The NVDB RESTful API allows to retrieve detailed data on the Norwegian public road system and its objects. In our work, this API is used to fetch a list of all road tunnel objects and to retrieve the relevant information about each tunnel objects (e.g., name, length, location and path coordinates).

Using the data provided, tunnel coordinates (i.e., latitude, longitude and altitude) in the WGS 84 coordinate system are obtained for each tunnel. Based on this, a rectangular bounding box is defined around the complete tunnel using two pairs of coordinates, which allows to fetch the tunnel map data from OSM using the Overpass API [39]. Afterwards, SUMO's *netconvert* tool is used to generate a SUMO network file from the OSM map file.

B. Mobility

In order to set up mobility scenarios in the tunnel, it is essential to identify the individual tunnels among all the tunnel edges obtained from OSM. To address this, an algorithm has been designed that finds the subsets of consecutive tunnel edges by searching for sequences of tunnel edges that are linked together by SUMO junctions. This algorithm can be run on any SUMO network to find individual tunnel sections.

Once the tunnels have been identified, a mobility scenario can be defined with a series of vehicles and routes. Each vehicle is assigned a route, which can be determined by a list of connected edges. For our basic experimental scenario, we define a single vehicle which drives from one end of the tunnel to the other. The vehicle begins the route from a full stop at one of the tunnel entrances and accelerates at a maximum of $2.6\,m/s^2$, which is SUMO's default acceleration for a passenger car. The vehicle never exceeds the tunnel's maximum speed, which is registered in the road edges imported from OSM. The simulation time step is 0.01 s, matching the IMU refresh rate.

C. Inertial Navigation

We use the IMU model provided by MATLAB [38], which allows to simulate the readings of the accelerometer, gyroscope and magnetometer in an IMU. The models for the inertial sensors can be customized according to physical parameters related to the electronics of the device, such as the resolution, offset bias, noise density and bias instability.

In this work, we use as reference the Bosch-BMI160 IMU [40], with noise density values of $180\,\mu g$ and $0.007\,^{\circ}/s$ for the accelerometer and gyroscope respectively, where g represents the gravitational acceleration – i.e., $9.8\,m/s^2$. The IMU runs at a sample rate of 100 Hz, and it does not include a magnetometer. Before feeding them into the INS model, vehicle position data is fit to a realistic kinematic trajectory to eliminate the potential artifacts of discrete mobility simulation.

D. Processing

From the INS simulation output, we obtain the positioning error by calculating the euclidean distance between the real position and the estimated position in each time step. To characterize the tunnel curvature (TC) and analyze its impact on the positioning accuracy, we perform the following calculations: first we compute the vehicle heading values (θ_i) using the pairs of (x_i, y_i) coordinates, as shown in 1; then we obtain the angular speed values by calculating the discrete derivative of the heading values and average it over the total number of samples (N), as shown in Equation 2.

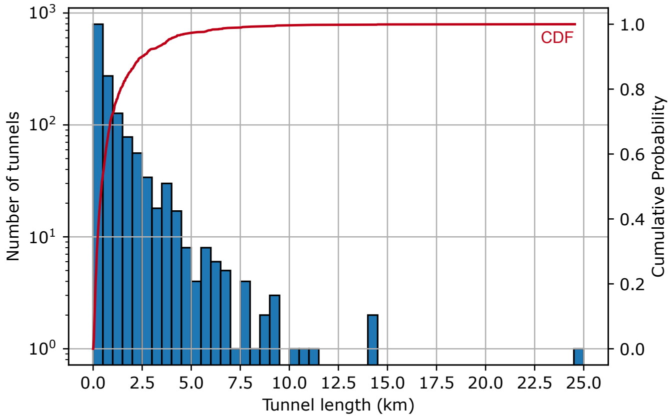

Fig. 2: Tunnel length distribution from NVDB data.

$$\theta_i = \arctan \frac{y_{i+1} - y_i}{x_{i+1} - x_i} \quad i = \{0, 1, 2, \ldots N-2\} \tag{1}$$

$$TC = \frac{\sum_{i=0}^{N-2} (\theta_{i+1} - \theta_i)}{N-2} \tag{2}$$

E. *Assumptions and Considerations*

In this work we make the following assumptions:

(1) The GNSS signal is completely blocked as soon as the vehicle enters the tunnel. This is the case in many tunnels going through mountains or under the sea.
(2) The effects of temperature in the readings of the IMU are not considered.
(3) The tunnel slope is not considered in the evaluations – i.e., positioning is only used for latitude and longitude estimations.
(4) The vehicle has no lateral movement within the road lanes.

IV. RESULTS

We present the results obtained using the tunnel dataset from the NPRA, which contains a total of 1526 tunnel sections with a length distribution shown in Figure 2. The length values of Norwegian tunnels appears to follow a negative exponential distribution: 73 % of the tunnels are less than 1 km long, and 98% of the tunnel sections are shorter than 5 km. The longest tunnels in the dataset are the 24.5 km long Lærdal tunnel and the 14.4 km long Ryfylke tunnel.

A. *Simulation bias*

Before presenting the experimental results, we show a comparison between the real readings of a commercial IMU and the simulated readings generated in MATLAB's IMU model in order to understand the simulation bias. Figure 3(a) and (c) presents the accelerometer and gyroscope readings in the 5.875 km long Byfjord tunnel in the region of Stavanger, Norway, captured from an iPhone 8 Plus located on a flat surface in the back seats of a bus going through the tunnel, in comparison with the simulated readings (b) and (d). The measurement was manually started as soon as the tunnel entrance was crossed on the southern entrance, and it was stopped right after leaving the tunnel on the northern exit. The plots only show the relevant readings for a ground vehicle: longitudinal and lateral acceleration and gyroscope yaw. Besides, Figure 4 presents the results of the INS simulation on top of real satellite map data.

The comparison shows that the real readings are significantly noisier, which is partly due to the heavy vibrations inside the bus. We also see more changes in acceleration due to congestion in the tunnel – which also increases the travel time –, while the simulated reading experiences no acceleration once it reaches the tunnel's max speed. We can observe how the gyroscope readings match the tunnel layout in both the real and simulated sensors: 1 left bend followed by 2 right bends and a straight section.

B. *IMU noise sensibility*

To understand the effect of the sensor noise, we have performed a sensibility analysis of these parameters for the Byfjord tunnel, shown in Figures 5 and 6. Results show that reducing the noise parameters by a factor of 10 and 100 does not improve the INS estimations significantly. On the other hand, increasing the errors by a factor of 100 introduces a noticeable performance degradation, as the position and heading estimations become less stable and more inaccurate.

C. *Positioning error in Kleppe, Larsberg and Ryfylke tunnels*

We have picked three tunnels to show detailed INS results. Two of them – Kleppe (Figure 7) and Larsberg (Figure 8) – are around 500 m long, but the second one is significantly curvier. The third tunnel is the Ryfylke tunnel (Figure 9), the second longest tunnel in Norway with a length of 14.4 km.

Results show that both positioning and heading errors tend to increase with a linear tendency over time as the vehicle goes deeper in the tunnel. Additionally, we observe sudden error offsets which happen when the vehicle is turning, due to sudden variations in lateral acceleration and angular speed. When comparing the results for the two tunnels with equal length, we observe that the Larsberg tunnel produces an error around 10 times bigger than the Kleppe tunnel. This indicates that the layout of the tunnel has an influence on the positioning estimation.

In long curvy tunnels such as the Ryfylke tunnel, positioning error grows to almost 2 km. We also observe that the deviations in curvy tunnel sections tend to make INS positioning fall behind the real position. This is a phenomenon we have also observed in real life tests: in some cases, the navigation applications still locate the vehicle inside the tunnel after having already left the tunnel and before recovering the GNSS signal.

D. *Evaluation of all Norwegian tunnels*

To analyze the performance trends of INS positioning, we present the maximum positioning error obtained for all Norwegian tunnel sections below 5000 m, which represent around 98 % of all the tunnel sections. We use a color map according to the tunnel's curvature value as presented earlier. The data points close to the origin have been reduced in size

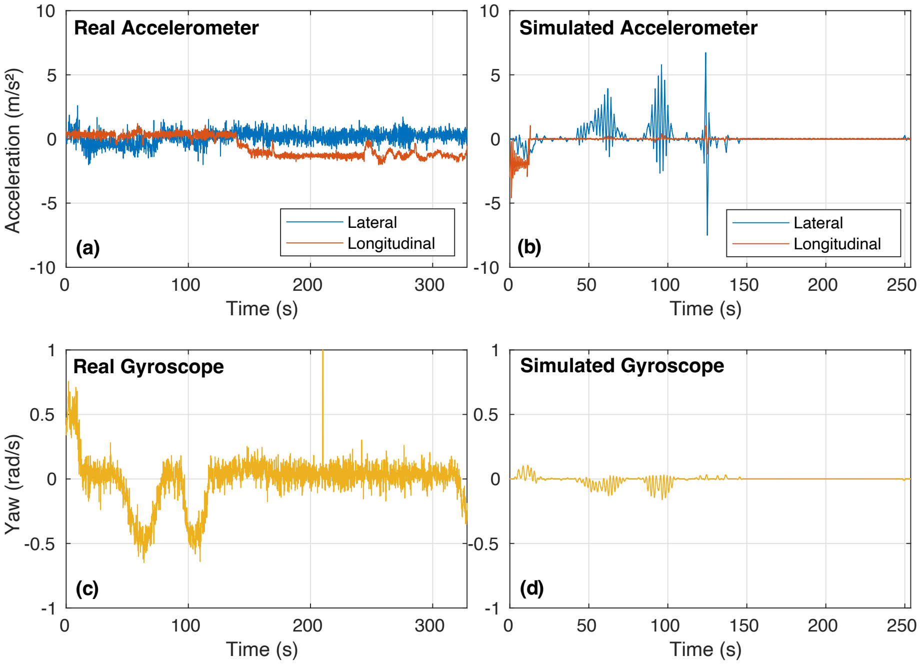

Fig. 3: Comparison of real and simulated IMU readings in the Byfjord tunnel.

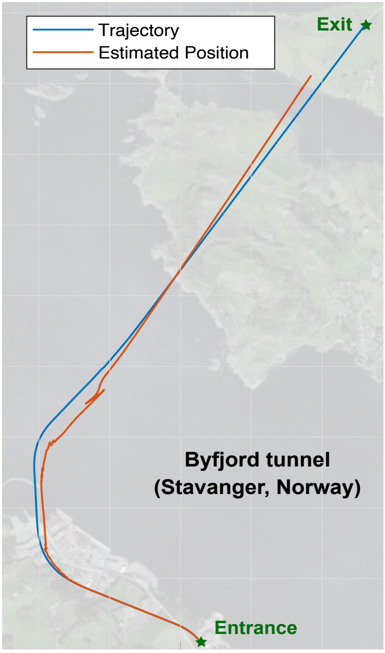

Fig. 4: INS results in Byfjord tunnel.

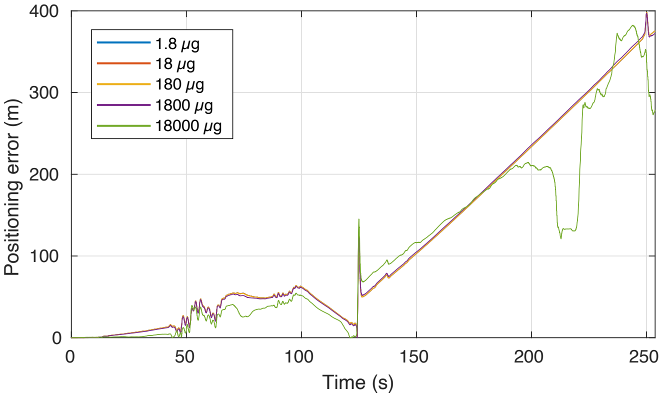

Fig. 5: Accelerometer noise sensibility test in Byfjord tunnel.

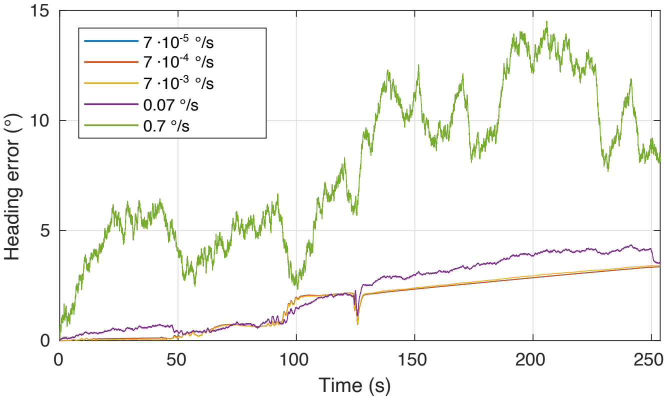

Fig. 6: Gyroscope noise sensibility test in Byfjord tunnel.

for better visualization, and errors above 500 m have been omitted.

Results show that the positioning error tends to increase as the tunnels become longer. However, there is some variability that is likely due to the tunnel profile. We observe that, for a given length range, tunnels with higher curvature – i.e., lighter colors – tend to produce larger errors.

To analyze the readiness of Norwegian tunnels for C-ITS applications, we compare these results with the positioning requirements presented earlier in the paper. We summarize them in Table II, which presents the number of tunnels meeting these requirements and the longest tunnel in each subset. Results show that around 52 % of the tunnels in Norway can meet the requirements of road navigation, and emergency response applications are met in around 44 % of the tunnels. However, less than 8 % of the tunnels can support cooperative maneuvers, and none of them can support collision avoidance.

C-ITS Application (Requirement)	No. of tunnels	Longest
Road Navigation (< 10 m)	722 (52.66 %)	4882 m
Emergency Response (< 4 m)	607 (44.27 %)	933 m
Emergency Break Warning (< 1.5 m)	447 (32.60 %)	729 m
Cooperative Maneuvers (< 30 cm)	106 (7.73 %)	115 m
Collision Avoidance (< 10 cm)	0	n/a

TABLE II: Amount of tunnels meeting the positioning requirements of the selected C-ITS applications.

V. CONCLUSION

This work has performed a preliminary evaluation of the accuracy of INS systems in the Norwegian road tunnel systems, using OSM map data, modeling vehicle mobility with SUMO and using MATLAB's IMU and INS models.

Results indicate that INS-based positioning in road tunnels suffers drifts which increase linearly over time, with occasional offsets occurring in curved tunnel sections. When looking at the whole Norwegian tunnel dataset, we observe that longer tunnels tend to experience larger drifts due to accumulation of errors, which can reach thousands of meters

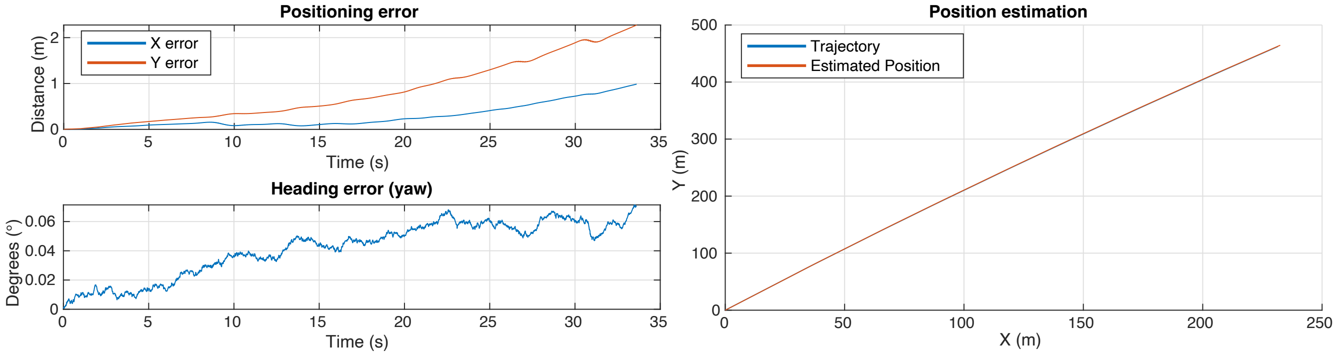

Fig. 7: Positioning results in Kleppe tunnel (Length: 517 m, TC: 0.1089).

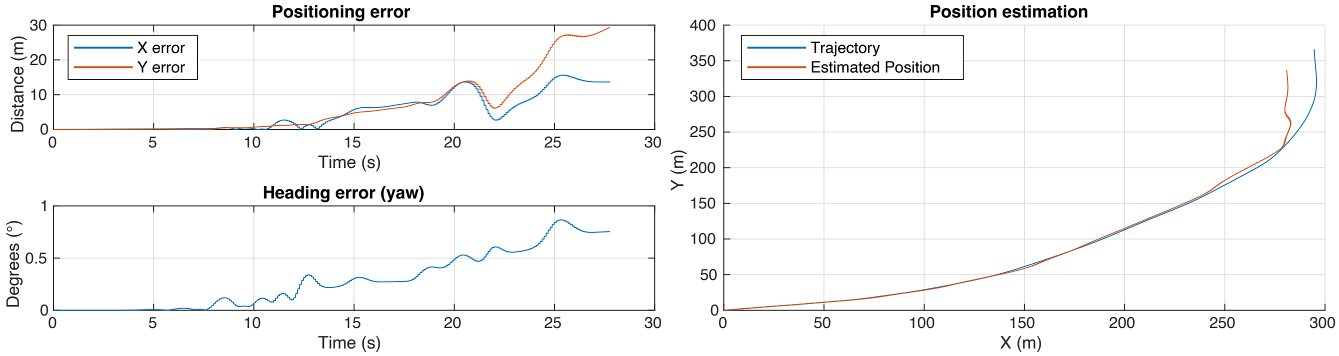

Fig. 8: Positioning results in Larsberg tunnel (Length: 523 m, TC: 1.5127).

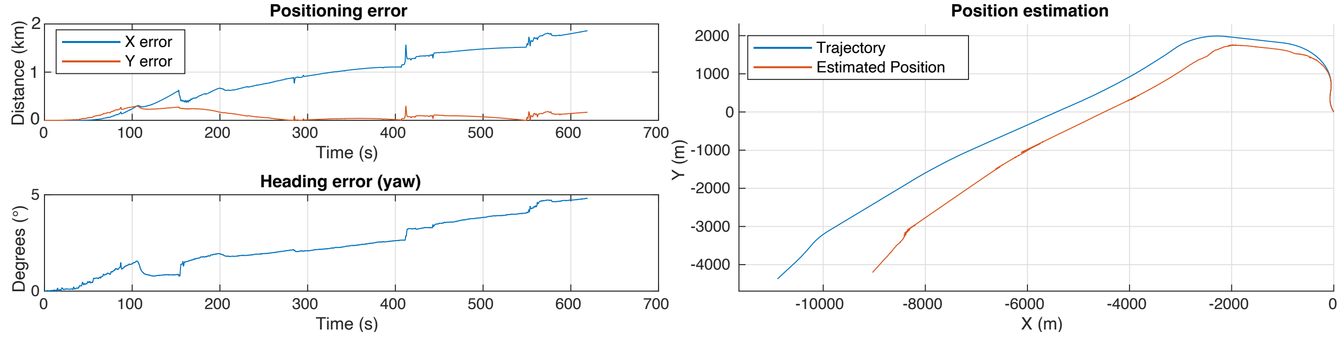

Fig. 9: Positioning results in Ryfylke tunnel (Length: 14.4 km, TC: 4.63384).

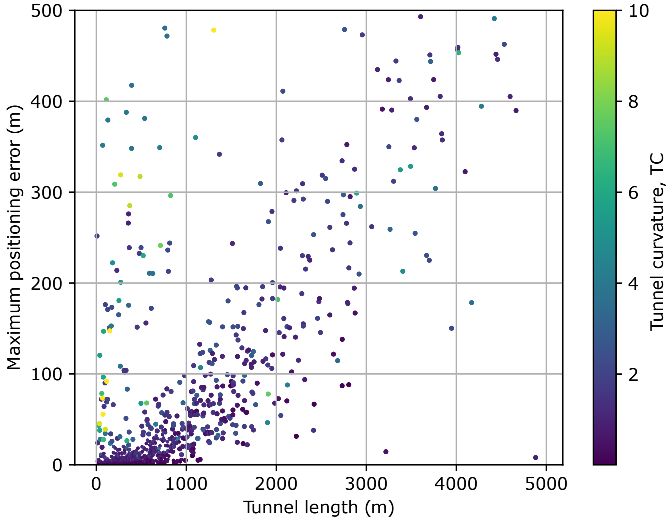

Fig. 10: Maximum positioning error of all Norwegian tunnels below 5000 meters.

in long tunnels. Results also show that curvy tunnels produce larger deviations than straight tunnels of similar length.

These results lay the foundations towards building a framework for developing cost-effective and reliable solutions for tunnel positioning. While our findings show that INS systems are far from ready to meet C-ITS application requirements in road tunnels, they can be great candidates for tunnel positioning if integrated with other solutions. Placing beacons or RSUs inside the tunnel strategically for correcting INS positioning errors (e.g., in sections where INS drifts grow significantly, such as bends) could drastically reduce deployment costs, making these solutions viable for future tunnel projects.

Future work will perform a more detailed study on how the dynamics of the IMU readings and its update rate impacts the INS positioning, using more advanced vehicle models and more realistic traffic behavior. It will also look into combining INS with other vehicle sensors (e.g., odometer), map data and indoor tunnel deployments, in order to design reliable and cost-effective positioning solutions for the tunnels of the future.

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