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Coordinator	*RISE/AstaZero*
Project Manager	*Felix Andlauer (felix.andlauer@ri.se)*
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Author(s)	Oscar Molina, Elena Haller, Frida Reichenberg, Felix Andlauer, Hui Chen
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Contents

Summary

This project explored how positioning uncertainty can be modeled to improve the realism and safety relevance of traffic and connectivity simulations. The work focused specifically on GNSS-related uncertainty and developed a simplified proof of concept in the Artery simulation framework, combining the agent-based traffic simulation tool SUMO with the communication network simulator OMNeT++. Positioning errors were represented through Gaussian noise, drift, and outliers, which were applied to an emergency vehicle warning scenario in which inaccurate positioning can influence vehicle responses and ultimately, the effectiveness of the investigated service.

The results show that even moderate positioning errors can significantly reduce service performance, increasing false alarms and missed alerts and thereby affecting both traffic efficiency and road safety. The study demonstrates that uncertainty-aware simulation is feasible and valuable for assessing connected mobility services under more realistic conditions. It also provides a basis for future research on larger-scale simulations, additional use cases, and mitigation strategies such as network-based relative positioning and integrated sensing and communication technologies.

Modeling Uncertainty for Safer Cooperative Mobility Simulations

1. Background

Knowing the state of vehicles and their surrounding environment is fundamental to intelligent transportation systems. Accurate and timely information such as vehicle speed, position, local traffic density and signal timing forms the backbone of cooperative applications like Cooperative Adaptive Cruise Control (CACC) and Green Light Optimal Speed Advisory (GLOSA), where even small deviations in timing or localization can significantly influence vehicle behaviour and safety margins.
In practice, however, acquiring this information is subject to non-ideal conditions, including communication delays, signal losses, and positioning errors. Despite their relevance, such effects are often simplified or neglected in current simulation frameworks (e.g., Veins, Artery), which tend to assume near-ideal conditions, leading to overly optimistic performance assessments and system designs that lack robustness against disturbance.
Therefore, there is a need to explicitly model and quantify these uncertainties. Incorporating realistic imperfections in communication, positioning, and sensing enables a more accurate evaluation of their impact on system performance and traffic dynamics, ultimately leading to more realistic and safety-relevant simulations.

2. Project set up

2.1 Purpose

The purpose of this pre-study is to investigate how uncertainties in positioning can be modeled in traffic simulations and to study how these uncertainties can influence different aspects of traffic safety and -flow. By introducing and quantifying positioning uncertainty, the project aims to improve the realism and safety relevance of cooperative mobility simulations, ultimately contributing to more reliable safety assessments and scenario design for connected vehicle research.

2.2 Objectives

The objectives of the project, as described in the application, were to explicitly model and quantify uncertainty factors in communication, positioning, and sensing relevant to cooperative mobility simulations. However, due to time constraints, the scope was narrowed to focus exclusively on positioning uncertainty. Within this scope, the work includes the identification of key positioning uncertainty parameters and traffic performance metrics, implementation of simplified positioning uncertainty modules, and exploration of a representative traffic scenario. The project aims to deliver a catalogue of positioning uncertainty factors and a proof-of-concept implementation.

2.3 Project period

2025-12-01 to 2026-05-31

2.4 Partners

The project involves three partners. RISE AstaZero serves as the coordinating partner, with Felix Andlauer as project manager. The additional partners are Halmstad Högskola and Chalmers University of Technology. The total granted funding amounts to 100,000 SEK, distributed as 25,000 SEK to RISE AstaZero, 50,000 SEK to Halmstad Högskola, and 25,000 SEK to Chalmers, all financed through the SAFER Idea Exploration program.

3. Method and activities

For implementing a simplified proof-of-concept (PoC), the open-source V2X simulation framework Artery was used. Artery combines the SUMO (Simulation of Urban MObility) traffic simulator with the OMNeT++ network simulator. Although Artery is generally capable of simulating a wide range of V2X communication technologies and standards, the partners agreed that modelling GNSS positioning uncertainty is sufficient to investigate the general feasibility of the chosen simulation tools.

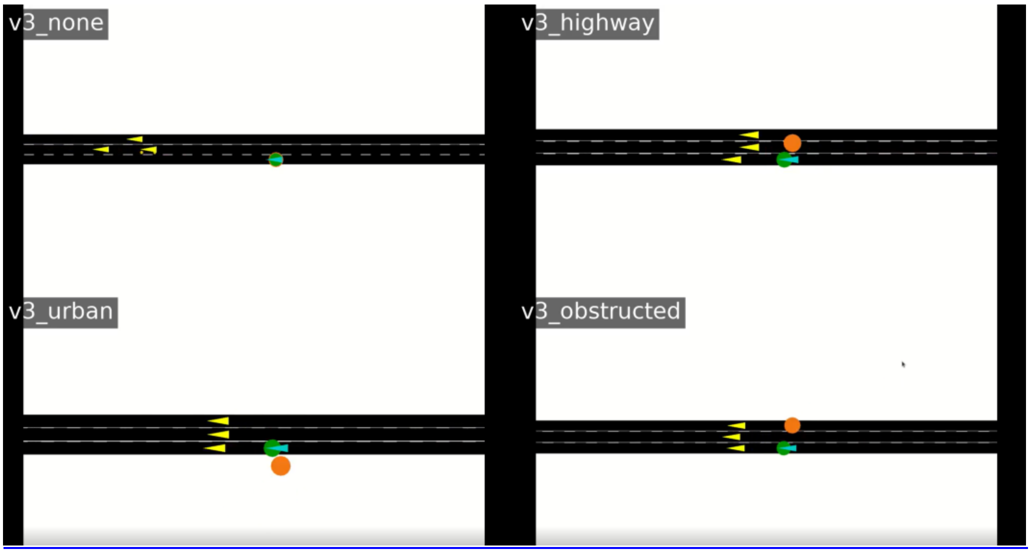
3.1 GNSS positioning noise modeling framework

To realistically simulate positioning errors, the measurement noise is decomposed into three main components: Gaussian noise, drift (i.e., bias) noise, and outlier noise:

- Gaussian noise represents baseline random measurement uncertainty. It is modeled as zero-mean white noise with standard deviation σ which varies depending on signal quality and satellite geometry: μ=0, σ = 1-5 m (1m - good conditions, 3m - typical GPS, 5m - urban degraded)
- Drift noise corresponds to slowly varying time-correlated biases $b_{\parallel}$ often caused by multipath effects or filtering errors. This bias is typically directional with a dominant component aligned with the street or motion direction: $\Delta x = b_{\parallel} \cos(\theta), \Delta y = b_{\parallel} \sin(\theta) + small\ b_{\perp}$.
- Outlier noise describes occasional large deviations due to signal loss, multipath spikes or receiver glitches, resulting in abrupt position jumps (5–20 m).

3.2 PoC use case: Emergency vehicle V2X, blocking cars scenario

Due to the limited scope of the project, only a very simplified PoC could be implemented. It demonstrates the general feasibility of the chosen tool chain to model different levels of uncertainty in GNSS positioning and to simulate how these positioning uncertainties influence the performance of a basic Emergency Vehicle Warning (EVW) service. Figure 1 below shows the scenario with an emergency vehicle (green triangle) and its actual position (green circle) broadcasting its "perceived" position (orange circle) to the traffic ahead (yellow triangles) and requesting the vehicle in the emergency vehicle's lane to move out of the way ("blocking cars scenario").



1: Basic PoC Use Case with four different disturbance/noise scenarios

4. Results and Deliverables

4.1 Scenario-based noise models

Positioning errors in GNSS systems arise from both global (location-independent) and local (location-dependent) phenomena. Location-independent errors originate from satellite-related factors, such as clock drift, orbital inaccuracies, and atmospheric delays (e.g., ionospheric and tropospheric effects), and tend to affect all receivers in a similar manner.

In contrast, location-dependent errors are driven by the surrounding environment and can vary significantly over short distances. These include effects such as signal obstruction, multipath propagation, and non-line-of-sight (NLOS) conditions. While such errors are most evident in clearly obstructed environments (e.g., tunnels or dense urban areas), they can also occur in open-sky conditions due to reflections from nearby objects.

This section focuses on modeling these location-dependent effects, as they are the primary source of variability and degradation in realistic positioning scenarios.

Highway Scenario

In open highway environments, satellite visibility is generally unobstructed, resulting in favorable geometry and predominantly line-of-sight (LOS) conditions. Errors are therefore small, isotropic, and largely uncorrelated.

Component	**Model**	**Typical values**
Random variance	Gaussian	σ = 1-3 m
Dynamic bias	No	-
Outliers	No (or rare, small)	- (5-10 m jumps)

Urban Scenario (Street Canyon)

Urban environments introduce significant multipath and non-line-of-sight (NLOS) effects due to buildings. Errors become larger, anisotropic, and often correlated with the street layout.

Component	**Model**	**Typical values**
Random variance	Gaussian	σ =5-10 m
Dynamic bias	Street-aligned $b_{\parallel}$ (random walk), some small $b_{\perp}$	3-10m, $b_{\perp}$ ~N(0,5–2 m)
Outliers	Poisson	10m (every 20-60 s) - 30 m (every 2-5 min) jumps

Obstructed Scenario (Tunnels, Dense Foliage, Parking Structures)

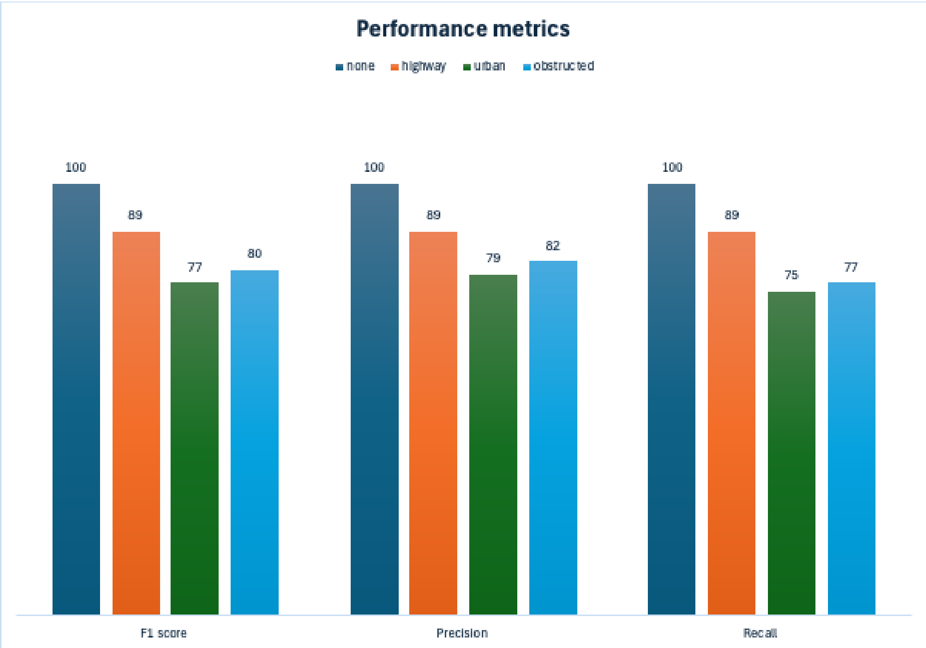
In highly obstructed environments, GNSS signals are severely degraded or unavailable. Errors are dominated by drift and large discontinuities rather than Gaussian noise.

Component	**Model**	**Typical values**
Random variance	No need (is dominated by others)	-
Dynamic bias	,	1-3 m random drift per timestep (m/s)
Outliers	Large, frequent + freezing	10 -30 m jumps every 5-10 s + freezes for 1-2 s

4.2 Simulation results

The following section summarizes the results from ten simulation runs per noise model (40 runs total) based on the following KPIs that measure the effectiveness and reliability of the service under the influence of positioning noise.

- Behaviour quality KPIs: Precision (ratio of true positive alerts to total generated alerts), Recall (ratio of true positive alerts to total actual “threats”), F1 score (harmonic mean of Precision and Recall), false alarms (percentage of triggered alerts that were incorrect) Missed alerts (Percentage of actual “threats” that the system failed to flag
- Noise Indicator KPIs: GNSS error mean, GNSS freeze
- Speed indicator: Emergency vehicle average speed (as a measure of the service’s general effectiveness



2: Positioning performance metrics for the four different noise models

Table 1: Summary of simulation results

Metric	Unit	none	highway	urban	obstructed
Precision		1.00	0.89	0.79	0.82
Recall		1.00	0.89	0.75	0.77
F1 score		1.00	0.89	0.77	0.80
False alarms	%	0.00	10.97	21.18	18.23
Missed alerts	%	0.00	11.06	25.10	22.63
GNSS error mean	m	0.00	2.53	10.79	12.86
GNSS freeze	%	0.00	0.00	0.00	18.02
Police average speed	km/h	110.27	58.55	59.64	80.52

5. Conclusions, Lessons Learnt and Next Steps

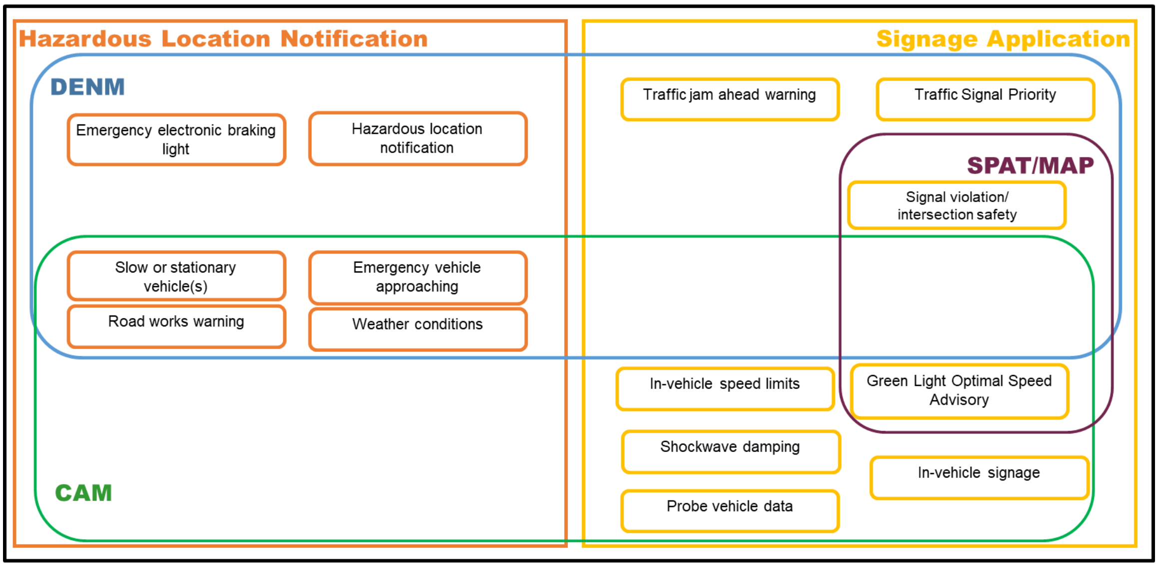
5.1 Conclusions

There are two main takeaways from this work. Firstly, it is now possible to integrate, monitor, and assess the effect of positioning uncertainty in traffic simulations at different scales. The only limitation, given the chosen simulation tool, would be computing power (as it is for any large-scale simulations). This gives the community a chance to assess the performance of current and upcoming services and applications that rely on positioning. Secondly, the effect of uncertainty on protocol performance might be so big that it can hinder not only traffic efficiency, but also road safety. This effect is visible in the small-scale simulations we performed on one use case, and more use cases need to be investigated at different scales to assess how significant the problem may become when future mobility becomes more pervasive.

These conclusions drive us to the lessons learned that are included in section 5.2, and to assess possible mitigations which we include in section 5.3. Furthermore, we provide a roadmap of possible next steps and lines of research. Finally, the main result of this project is the groundwork for a future application for a project where additional partners can be involved – e.g., Trafikverket, through their FOI program – and stakeholders in the connected mobility industry as well as car and truck OEMs.

5.2 Possible Impact on Road Safety and Traffic Efficiency

The fact that even in open spaces positioning accuracy is imperfect can affect what road users perceive as a threat to road safety or a hurdle for the timely completion of their trips. Furthermore, when these trips have a myriad of natures and purposes (e.g., a commute, a leisure trip, a blue-light car responding to a call), the number of combinations of interactions where wrong positioning information can affect decision-making abilities become so large that it helps to map them across the different deployment phases of V2X technology. In this report, we follow the CAR 2 CAR Communication Consortium's categorization (CAR2CAR, 2019) that distinguishes different deployment phases, from simple status sharing (referred to as "Day 1") to intent & perception sharing ("Day 2") and finally all types of coordinated maneuvering ("Day 3"). For now, we will only consider services for Day 1 which are deployed on many public roads around the world (Haller, 2026).



3: Day 1 services and ETSI ITS messages

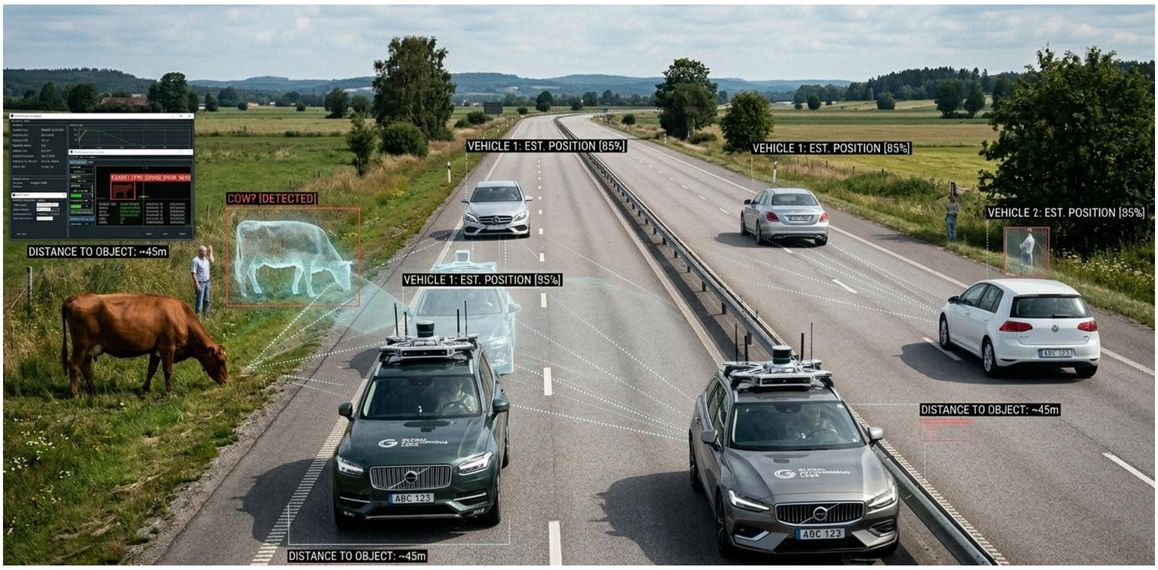
Figure 3 shows the connectivity-based services in the framework of the first release of the ITS protocol stack defined by the European Telecommunications Standards Institute (ETSI). These services are enabled by messages generated by vehicles – e.g., Cooperative Awareness Messages (CAMs), Decentralized Environmental Notification Messages (DENMs) – or by the infrastructure, e.g., Signal Phase and Timing (SPaT) or Map messages. Each of these messages has a set of data structures where the position of an event is shared, and they may rely on the node's own positioning information to alert other nodes of a danger. For example, a DENM includes the position of the generating vehicle as well as the relevance area of an event (i.e., where the event occurs). These can be two different positions, and the relevance area might even be set manually depending on the application generating the message (e.g., in the same fashion alerts in the route planning app WAZE are set manually). However, let us consider a case when a DENM that alerts other users of a patch of black ice on the road (hazardous location notification) might be triggered automatically by the sensing systems in the vehicle. The car will set the relevance area to the position at which the vehicle sensed the slippery part of the road. The same case may occur with emergency electronic braking light applications, when it is not viable to set the relevance area manually and the nodes rely on their own positioning systems which can be inaccurate.

Table 2: List of relevant "Day 1" services and a positioning error's influence on safety and traffic efficiency

Service	Positioning	Risk to road safety or traffic efficiency
Emergency electronic braking light	Automatic	Safety: • Wrong lane or direction
Roadworks warning	Automatic/ Manual	Safety: • Wrong lane or direction Efficiency: • Unnecessary re-routing
Slow or stationary vehicle	Automatic/ Manual	Safety: • Wrong lane or direction
Hazardous location notification	Automatic/ Manual	Safety: • Wrong lane or direction • Unnecessary triggering of risky maneuver Efficiency: • Unnecessary re-routing
Emergency vehicle approaching	Automatic/ Manual	Safety: • Wrong lane or direction • Unnecessary triggering of risky maneuver Efficiency: • Unnecessary changes in vehicle speed • Emergency vehicle delay
Weather conditions	Automatic/ Manual	Efficiency: • Unnecessary rerouting
Traffic jam ahead warning	Automatic	Safety: • Wrong lane or direction • Untimely braking Efficiency: • Unnecessary re-routing
In-Vehicle speed limit	Automatic	Safety: • Untimely speeding down or up Efficiency: • Rule violation
Shockwave damping	Automatic	Safety: • Wrong lane or direction • Untimely braking Efficiency: • Unnecessary re-routing
Probe vehicle data	Automatic	Not applicable
Traffic signal priority	Automatic / Manual	Safety: • Untimely speeding down or up • Untimely braking Efficiency: • Unnecessary re-routing • Unnecessary yielding
Signal violation	Automatic	Efficiency:

		• Incorrect identification of rule violations
GLOSA	Automatic	Safety: • Untimely speeding down or up • Untimely braking
In-vehicle signage	Automatic	Safety: • Untimely speeding down or up Efficiency: • Rule violation • Unnecessary re-routing

The table above shows a summary of the so-called "Day 1" services and the risks that would come from sending or receiving wrong positioning information in a CAM, DENM or SPAT. Positions can be needed for one or all the interacting nodes in some services, e.g., a slow or stationary vehicle can self-report its position, but a GLOSA interaction requires the vehicles to have reliable information to decide whether to accelerate or decelerate. The table describes, if positions are set automatically (i.e., based on the node's positioning and time services), or if they can be set manually reported by a driver or, in case of intelligent vehicles, by automation sourcing information from alternative services (e.g., with camera-based "geoguessing").



4: Collective Perception scenario with uncertain location

The risks increase, however, with Day 2 and beyond services. Vehicles equipped with Collective Perception (CP) perform object and event detection and broadcast this information to connected neighbors. This allows, theoretically, for connected vehicles that lack sensors like radar, lidar, or cameras to become aware of objects present in their surroundings by sourcing information from neighbors. Figure 4 shows a scenario where the black vehicle thinks it is located 6 meters behind its actual position, thus, its sensors report the cow as being six meters behind, luckily, still outside the road. However, if there was also a lateral error, the cow could be (falsely) reprted as being on the road. Furthermore, a cow that is on the road can be reported as being outside. The dark-gray vehicle is equipped with additional sensors, so, it can give more weight to what it actually sees, but the light-gray vehicle approaching, if connected, would rely on the information provided by the vehicles with sensors. It would probably receive conflicting information or think that there actually two cows present in the scenario.

Days 3 and 4 services can also be affected by uncertainty. On Day 3, vehicles are expected to share their intentions and, on Day 4, vehicles are expected to coordinate their maneuvers. For the case of pure connected mobility, i.e., not assuming full automation of driving or other sensing capabilities, the latent risk is to use unreliable information to predict one's trajectory and, thus, broadcast unreliable information. However, it is expected that network access technologies will be available and deployed for Days 3 and beyond. These access technologies will operate at bands where network-based relative positioning or even Integrated Sensing and Communications (ISAC) can be relied on (Haller, 2026). We will explore these in depth in the next section.

5.3 Network-based mitigations

Day 1 services and the deployments based on Release 1 of the ETSI ITS protocol stack consider the use of the 5.9 GHz band either by cellular- or WiFi-based technologies. For the case of WiFi technologies, ETSI ITS-G5 (based on IEEE 802.11p) does not consider the use of Multiple Input Multiple Output (MIMO), thus, a single antenna is used for communications. Future releases (e.g., IEEE 802.11bd) not only support MIMO, but also the use of the 60 GHz band, which could potentially enable ISAC capabilities. While MIMO and ISAC are natural network-based mitigations for uncertainty in positioning, we can consider other possible mitigations for currently existing and upcoming network technologies.

Table 3: Possible positioning error mitigation methods based on relative vehicle positioning

Method	Requirements	Candidate technologies
Received Signal Strength Indicator (RSSI)	Single antenna and line of sight (LoS)	802.11p, 802.11bd, 5G-NR, 6G, UWB
Channel State Information (CSI)	Single antenna and LoS	802.11p, 802.11bd, 5G-NR, 6G, UWB
Fine Time Measurements (FTM)	Single antenna and LoS	802.11p, 802.11bd, 5G-NR, 6G, UWB
Angle of Arrival (AoA)	MIMO and LoS	802.11bd, 5G-NR, 6G, UWB
Time of Arrival (ToA)	Single antenna, synchronization, and LoS	802.11p, 802.11bd, 5G-NR, 6G, UWB

The table above shows a summary of mitigations based on relative positioning between nodes. Let us consider a case where two vehicles are within range of each other and exchange information using messages. However, the position included in that message has a degree of uncertainty that can be reduced if the vehicles are able to measure their relative positioning. RSSI and CSI can be used in existing deployments and use currently existing headers, since a CAM or a DENM must be encapsulated as, e.g., a WiFi frame for 802.11p which has RSSI in their preamble. Thus, if some characteristics about the nodes are standardized, one can use information about the power of the received frame, and which subcarriers are being used to determine the distance between the transmitter and the receiver. For the case of FTM, existing deployments would need an update to use, e.g., a parallel channel, to send beacons and determine how far nodes are from each other using an FTM protocol (e.g., measuring the round-trip time of a packet and calculating the distance as a function of the propagation delay). Finally, AoA and ToA are widely used in Ultra-wide Band (UWB) for two-way ranging. They use information about the difference in phase at which a frame arrived at the multiple antennae in MIMO (for AoA) and then use this in conjunction with the signal strength to calculate at least 2D relative positioning information. For the case of ToA, previous synchronization between the nodes is required.

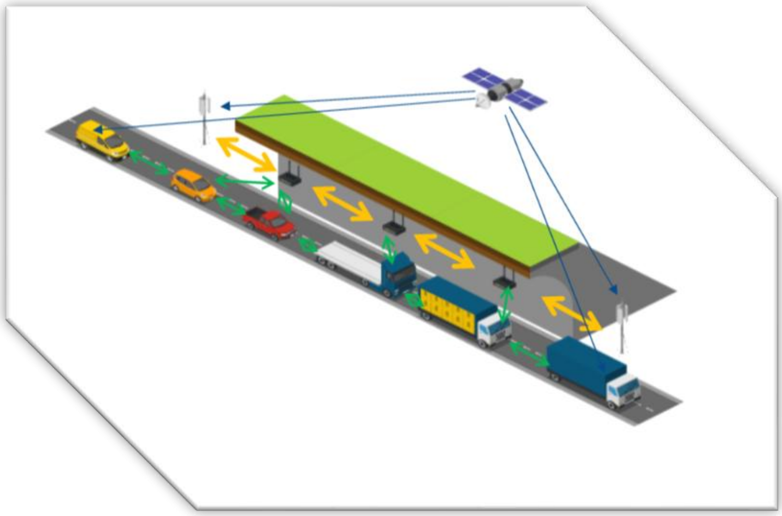


Figure 5. Network-based positioning error mitigation for obstructed GNSS

Figure 5 presents a possible scenario for the mitigation technologies, regardless of which access technology is used. We start with an obstructed GNSS scenario where the vehicles inside the tunnel (shortened and cut longitudinally for visibility) cannot obtain their coordinates from the satellite. However, they can 1) perform ranging against each other using vehicle-to-vehicle communications (green arrows) and any of the methods from Table 3 use the infrastructure to convey an approximation of their absolute position (yellow arrows).

For all the mitigations, further work needs to be performed to find trade-offs and limitations. For example, media phenomena such as multipath will create scenarios where messages are received from reflections instead of the line of sight, which will hinder the ability of the nodes to calculate the distance accurately. Thus, it is with ISAC-enabled technologies, which work on the 60 GHz spectrum and can beamform, where these techniques might find a niche to perform. However, this is still an open question for the research community in vehicular communications.

5.4 Future lines of research and development

In strict Connected Safety terms, the two most obvious lines of research and development are network-based relative positioning and ISAC. It is important to consider both existing and emerging network technologies. Preliminarily, we are performing work that has found the effect of multipath in single-antenna deployments and its unsuitability for ranging in, e.g., deployments of IEEE 802.11 without MIMO. Furthermore, we have measured positioning errors in ideal conditions (i.e., open air, good atmospheric conditions) and its effect in a Day 1.5 service – the Vulnerable Road User awareness basic service.

We plan on narrowing down the two main lines according to the theoretical capability of each mitigation and its possibility to operate in current or upcoming deployments. For example, we discard RSSI and WiFi-based FTM after our previous experiences assessing it in cycling scenarios (Ondrejov, 2025). However, CSI seems like a feasible approach for current deployments (e.g., 802.11p, ETSI ITS-G5). Methods using AoA and ToA are also feasible if we consider UWB a current deployment. The penetration rate for UWB is already nearing one third of sold premium vehicles and it is even higher for mobile phones(IntelMarketResearch, 2026). This means that early adopters are already there, which may also occur with 6G technologies that can also use CSI, AoA and Toa.

Furthermore, ISAC is a crucial feature of 6G deployments, and it is a possibility for 802.11bd. While ISAC enables communication equipment to perform sensing functions, it is also a possibility to use currently deployed radars during part of their duty cycle to perform communication tasks. These options are part of the emerging communication technologies of our future work, and require a narrowing down of specific use cases, e.g., technologies that form beams might be suitable for bumper-to-bumper communications in platoons when minimal beam steering is necessary, but not for infrastructure-to-vehicle communications when beam steering might create disruptions.

Table 4

Line	Work	Required partners
CSI	Assessment of CSI ranging for vehicular communications	V2X equipment developers Cellular equipment developers
AoA and ToA	Assessment of AoA and ToA for UWB, WiFi and Cellular	V2X equipment developers Cellular equipment developers UWB chip developers
ISAC	Assessment of the sensing and ranging capabilities of emerging communication technologies	Communication equipment developers
	Assessment of the communication capabilities of existing ranging technologies	OEMs (radar)

Collaboration with traffic authorities is also crucial, since it is them who should steer the work towards realistic use cases and feasible deployments. That is why the work on these lines can be divided into packages where specific use cases are defined, since not all applications will have the same requirements or assumptions. For example, intelligent vehicles might be assumed to be connected in the future, but pedestrians and cyclists may not.

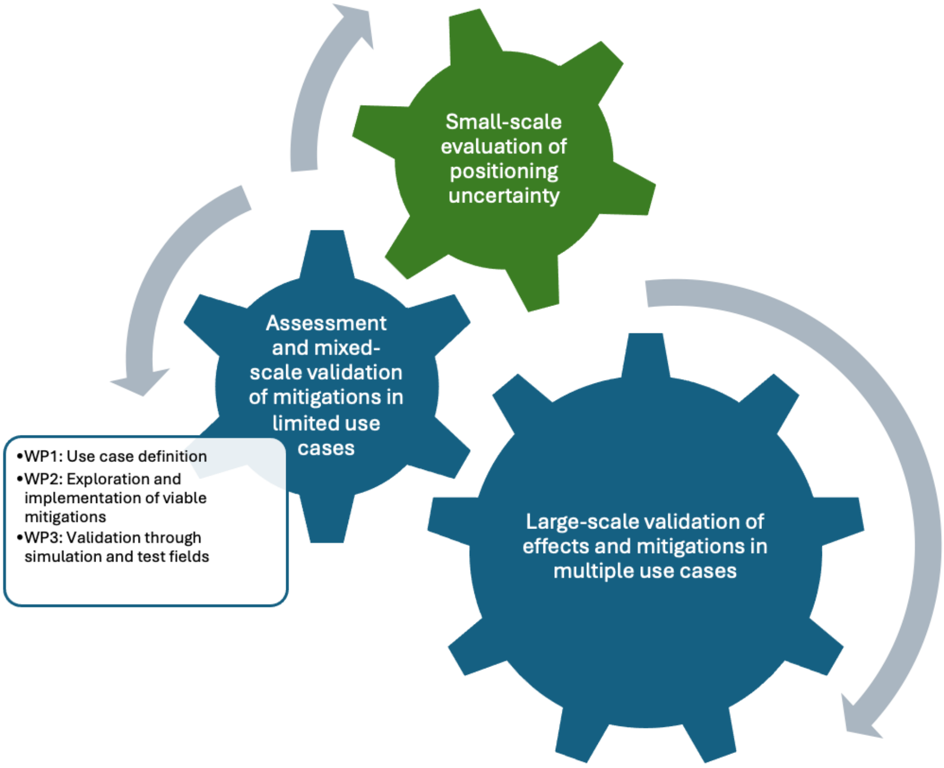


Figure 6. Line of research and development progression

Fig. 6 shows how this project – represented by the green gear – relates to future research and development work. The next gear is a project that attempts to validate our findings on larger scales while also exploring the mitigations we proposed. It is important to develop a tool that – in the same way the one we developed allows to assess effects – allows researchers to test mitigations at different (and even multiple) layers of the protocol stack. Three potential work packages of a larger future project have already been identified, where we rely on simulations for large-scale scenarios and field tests in smaller scales. However, the long-term goal is to have collaborations at larger levels with partners from the industry, authorities, and research, as well as partners coming from different regions.

6. Dissemination and Publication

This final report will be available for publication through SAFER's channels. Furthermore, the project results are expected to form a basis for future applications for larger follow-up initiatives. Possible next steps include applications to the "möjliggöra" portfolio within Trafikverket's FoI fund, to relevant calls within Vinnova's FFI program, and to suitable Horizon Europe calls and partnerships related to connected, cooperative, and automated mobility, road safety, and smart transport systems.

7. Acknowledgement

The authors would like to acknowledge the support provided through the SAFER Idea Exploration program, which made this pre-study possible.

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