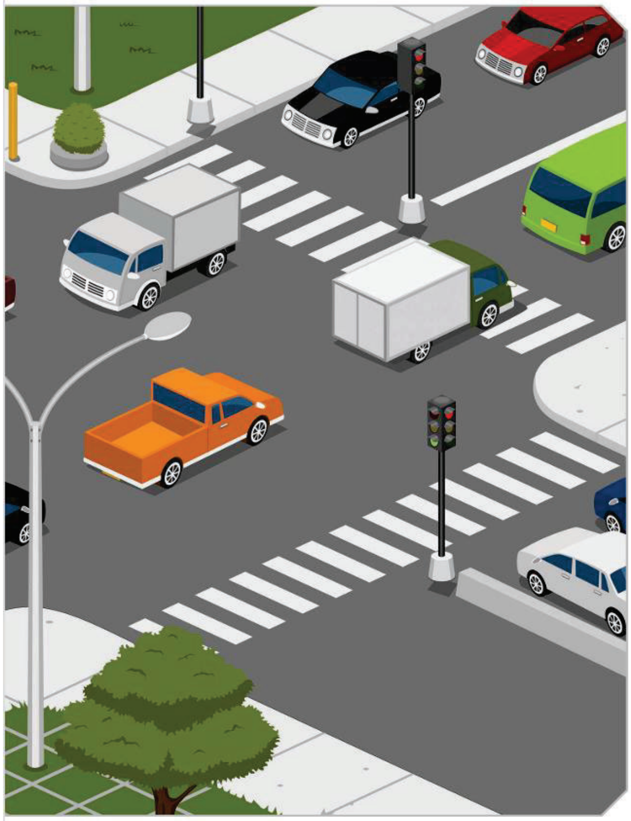
Uncertainty-aware and safety-enhanced management of CAVs for safer mixed traffic

Public report



Project within FFI: Traffic-safe automation - FFI Spring 2024

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Fordonsstrategisk
Forskning och
Innovation

Content

FFI in short

FFI, Strategic Vehicle Research and Innovation, is a joint program between the state and the automotive industry running since 2009. FFI promotes and finances research and innovation to sustainable road transport.

For more information: www.ffisweden.se

1. Summary

This project focuses on enhancing the safety of connected and autonomous vehicles (CAVs) operating within complex mixed traffic environments, where both human-driven vehicles (HDVs) and CAVs coexist. In such scenarios, CAVs are subject to multiple sources of uncertainty, including unpredictable human behavior, incomplete or delayed communication, and potential cyber threats. To address these challenges in a systematic and comprehensive way, the project concentrated on two principal objectives. The first was to develop models and techniques for perceiving and quantifying uncertainties that arise in mixed traffic. The second was to establish adaptive and robust operational control strategies for CAVs that can enhance safety under uncertain conditions.

In pursuit of the first objective, the project developed advanced models to capture and quantify the variability inherent in human driving behavior and environmental complexity. A probabilistic trajectory prediction framework was proposed to incorporate behavioral heterogeneity among human drivers. By learning from historical trajectory data and extracting driver-specific behavior features, the model significantly improves the accuracy of future movement predictions. This contributes to the anticipation of potentially dangerous interactions and allows CAVs to plan more cautiously in uncertain surroundings. In addition, a vision-based traffic risk estimation framework was established to quantify human-perceived risk using features extracted from traffic scenes. The system was trained using human-labeled risk scores and demonstrates the ability to distinguish between scenes of varying perceived safety. These models enable real-time identification of high-risk scenarios and form a foundation for risk-aware CAV operation. The project also addressed communication-related uncertainty, which arises from issues such as packet loss and delayed information exchange in V2V communication systems. This type of uncertainty can lead to discontinuities in reference trajectories and provoke unstable responses in CAV control systems. To mitigate the resulting transients and suppress instability, a trajectory smoothing method was developed based on a variant sigmoid function. This strategy reduces the demand on communication bandwidth and ensures that trajectory tracking remains smooth and safe, even under degraded communication conditions. These contributions jointly strengthen the perception and quantification of uncertainties affecting CAV safety in real-world driving environments.

To meet the second objective, the project delivered a set of methods that emphasize adaptive planning and control under uncertainty, and validated them through simulation-based experimentation. A trajectory planning and signal coordination strategy was developed for CAVs navigating through dynamic urban intersections. This method incorporates vehicle-level dynamics into intersection-level decision-making to manage uncertainty in traffic flow and ensure both stability and safety. It enables CAVs to adjust their trajectories in response to evolving traffic conditions and promotes coordinated behavior in mixed traffic streams. In addition to planning, the project also proposed a control strategy tailored to bidirectional platoons of CAVs. This adaptive control method explicitly accounts for challenges such as actuator saturation and discontinuous trajectory inputs caused by communication failure. The control framework incorporates both internal

uncertainties, including model parameter variability, and external uncertainties, such as unpredictable HDV maneuvers or information delays. By using an adaptive mechanism to adjust control inputs in real time, the method ensures that CAVs can maintain tracking performance and inter-vehicle stability despite uncertain and evolving operational conditions. All developed methods were implemented and evaluated in a simulation environment built on the CarSim platform. This environment provided a realistic and controllable setting to validate control and planning strategies under a wide range of traffic conditions, behavioral variations, and uncertainty levels. The simulation results confirmed the effectiveness of the proposed methods in improving safety, stability, and responsiveness of CAV operations in heterogeneous traffic environments.
The research outcomes contribute to the advancement of safety-aware autonomous driving technologies and lay a strong foundation for future experimental validation and large-scale deployment of CAV systems in real-world scenarios.

2. Sammanfattning på svenska

Detta projekt syftar till att förbättra säkerheten för uppkopplade och autonoma fordon (CAV) som verkar i komplexa trafikmiljöer där de samexisterar med mänskligt framförda fordon (HDV). I sådana sammanhang utsätts CAV för flera typer av osäkerhet, inklusive oförutsägbart mänskligt beteende, ofullständig eller fördröjd kommunikation samt potentiella cyberhot. För att systematiskt hantera dessa utmaningar har projektet fokuserat på två huvudsakliga mål. Det första målet var att utveckla metoder för att uppfatta och kvantifiera osäkerheter som uppstår i blandtrafik. Det andra var att utforma adaptiva och robusta kontrollstrategier som stärker CAV:s förmåga att hantera dessa osäkerheter på ett säkert sätt.
För att uppnå det första målet utvecklades avancerade modeller som fångar och kvantifierar variabiliteten i mänskligt körbeteende och omgivningskomplexitet. En probabilistisk trajektoriprediktionsmodell togs fram där hänsyn tas till beteendevariationer mellan olika förare. Genom att lära från historiska kördata och extrahera individanpassade beteendemönster förbättras precisionen i prediktionerna, vilket möjliggör säkrare planering för CAV i osäkra situationer. Dessutom utvecklades en visionsbaserad modell för att uppskatta trafikrisker utifrån mänsklig upplevd säkerhet. Med hjälp av maskininlärning och bildanalys kunde systemet identifiera scenarier med hög risk och därmed stödja proaktivt beslutsfattande. Projektet hanterade även kommunikationsrelaterad osäkerhet, som uppstår till följd av paketförlust och informationsfördröjningar i V2V-kommunikation (vehicle-to-vehicle). Detta kan leda till diskontinuerliga referensbanor och instabil fordonstyrning. För att dämpa sådana övergångsfenomen och förbättra säkerheten utvecklades en metod för banutjämning baserad på en modifierad sigmoide funktion. Denna strategi reducerar både behovet av kommunikationskapacitet och instabilitet i kontrollsystemet, vilket säkerställer säker manövrering även vid försämrad kommunikation.
För det andra målet levererade projektet ett antal metoder med fokus på adaptiv planering och kontroll under osäkerhet, validerade genom simuleringsbaserad testning. En planeringsstrategi med signalkoordinering togs fram för CAV i dynamiska korsningsmiljöer. Genom att integrera fordonens rörelsedynamik med beslut på

korsningsnivå uppnås ökad robusthet, stabilitet och säkerhet i blandade trafikflöden. Utöver planering utvecklades en adaptiv styrmetod för dubbelriktade fordonsplutoner. Metoden tar hänsyn till både mättnad i aktuatorer och diskontinuerliga banreferenser som orsakas av kommunikationsbortfall. Kontrollramverket integrerar både interna osäkerheter (till exempel variationsrika fordonsparametrar) och externa störningar (såsom oförutsägbara manövrar från HDV och informationsfördröjning). Genom realtidsjustering av styrsignaler med hjälp av adaptiva mekanismer kan CAV upprätthålla stabilitet och säkerhet trots föränderliga och oförutsägbara förhållanden. Samtliga metoder implementerades och testades i en simuleringsmiljö baserad på Carsim-plattformen. Denna miljö möjliggjorde omfattande utvärdering under olika trafikförhållanden och osäkerhetsnivåer. Resultaten visade att de föreslagna metoderna effektivt förbättrar säkerheten och robustheten i CAV:s funktion i blandad trafik.
De integrerade forskningsresultaten bidrar till utvecklingen av säkerhetsmedveten autonom körteknik och skapar en stark grund för framtida experimentella valideringar och storskalig implementering i verkliga trafikmiljöer.

3. Background

The deployment of CAVs holds great promise for improving traffic efficiency, reducing emissions, and enhancing road safety. However, in the near to medium term, CAVs will operate in mixed traffic environments, where they must coexist with a wide range of HDVs. Unlike CAVs, which follow algorithmic control rules and communicate through vehicle-to-everything systems, HDVs exhibit highly variable and often unpredictable behaviors that are influenced by individual driving styles, attention levels, and context-specific decisions. This heterogeneity introduces significant challenges to achieving safe and robust autonomous driving in practice. Another challenge is the presence of uncertainty in both sensing and communication. While V2V and V2I communication technologies aim to enhance situational awareness and coordination, they are prone to imperfections such as packet loss, latency, and even malicious cyberattacks. These imperfections can degrade the reliability of shared information and cause discrepancies in perceived traffic conditions among vehicles. In turn, this can affect control decisions and lead to unsafe outcomes, particularly in dynamic or congested traffic environments. Existing CAV control frameworks often rely on idealized assumptions about perfect communication, known system dynamics, or fully observable environments. In reality, these assumptions are rarely satisfied. Moreover, many traditional approaches focus on performance optimization without explicitly addressing safety risks under uncertainty. There is a clear need for CAV systems that not only optimize operation in nominal conditions but also adapt to real-time uncertainty and ensure safety under degraded information or adverse events. The background and motivation underscore the necessity of this research, particularly as the complexity of traffic systems grows and the expectations for autonomous vehicle safety become increasingly stringent. To address these gaps, this project investigates a comprehensive framework that integrates uncertainty perception, quantification, and adaptive control for safer CAV operation in mixed traffic. By combining probabilistic modeling, behavior-aware trajectory prediction, robust control design, and simulation-based validation, the project aims to enhance the readiness of CAV technologies for real-world deployment.

4. Purpose, research questions and method

The purpose of this project is to enhance the safe operation of CAVs in mixed traffic environments by addressing the critical uncertainties that arise from interactions with HDVs, communication disturbances, and incomplete environmental observability. The research aims to develop a cohesive framework that integrates uncertainty perception, quantification, adaptive control, and validation through simulation, ultimately supporting safer deployment of CAVs in complex real-world scenarios.

The project is structured around three central research components:

(1) Active Environment Perception and Uncertainty Quantification

This component aims to enable CAVs to proactively perceive and quantify uncertainties from their surroundings in real time. Key research questions include:

- How can we model and represent the heterogeneity of human driving behavior in a personalized and data-driven way?
- How can communication-related uncertainties (e.g., packet loss, signal delays, malicious attacks) be detected and quantified?
- How can perceived risk be estimated through scene-level understanding?

To address these questions, the project employed the following methodological approaches:

- Probabilistic trajectory prediction models were designed using LSTMMD-DBV (long short-term memory and mixture density networks with driving behavior vectors) architectures, integrating personalized driving behavior features to capture the heterogeneity of HDVs.
- Shapley Additive Explanations were used to interpret the learned behavior features and validate model explainability.
- Computer vision-based traffic scene analysis was used to extract physical indicators (vehicle count, proximity, motion) for training risk estimation models via random forest regression.
- Statistical modeling was applied to communication data to represent uncertainty patterns, including detection of abnormal information loss or delay.

(2) Uncertainty-aware Operation Control of CAVs

The second research component focuses on the design of control and planning methods that explicitly incorporate uncertainty into vehicle behavior, enabling robust and safe decision-making even under degraded conditions. Key questions include:

- How can CAVs maintain safe control under actuator limitations and uncertain trajectory references?
- How can adaptive control systems handle internal model errors and external disturbances?

- How can vehicle-level control be coordinated with network-level signal systems to stabilize heterogeneous traffic flows?

The following methods were developed to answer these questions:

- Adaptive control frameworks based on coupled sliding mode control were designed to address actuator saturation and discontinuous inputs, ensuring string stability in bidirectional platoons.
- A variant sigmoid smoothing technique was developed to mitigate transients caused by trajectory discontinuities, reducing control oscillations and improving safety.
- Robust feedback structures were embedded to enable real-time adjustment of control parameters in response to observed uncertainty in vehicle dynamics and surrounding behavior.
- A mixed-integer linear programming (MILP) model was formulated to coordinate vehicle trajectories and signal phase transitions in a networked intersection environment, promoting flow stability under uncertain conditions.

(3) Simulation, Verification and Demonstration

The third component involves rigorous evaluation of the proposed methods in controlled simulation environments to ensure their effectiveness for future real-world implementation. Core research questions include:

- How can simulation platforms be configured to capture real-world uncertainty scenarios?
- How do the proposed algorithms perform under varying traffic densities, uncertainty levels, and failure cases?

The project employed the following methods:

- A simulation environment was built using CarSim, integrated with MATLAB/Simulink and SUMO where appropriate, to test the interaction between CAV dynamics and traffic control algorithms.
- Scenario-based validation was performed by varying communication quality, driver behavior, and traffic patterns to test the robustness of planning and control.
- Key performance metrics such as trajectory tracking accuracy, string stability, risk score prediction, and energy efficiency were used to benchmark system performance.
- Results from simulation were cross-referenced with theoretical expectations, and selected modules were prepared for future deployment on small-scale test vehicles.

5. Objective

This project mainly aims to achieve the following two objectives to enhance safe operation of CAVs in real-world complex traffic environment:

- *Uncertainty perception and quantification in mixed traffic scenarios to identify and quantify risk.* This objective aims to develop advanced perception and quantification models that can predict and quantify the uncertainties that may result in safety issues of CAVs, including uncertain behavior of human drivers and uncertainty due to unreliable/delayed communication and malicious cyber-attacks on vehicle communication networks.

- *Safety-enhanced and uncertainty-aware operational control of CAVs in mixed traffic environments.* This objective aims to develop adaptive and robust operation control methodologies for CAVs in mixed traffic including cooperative decision-making and real-time adjustments of control based on perceived/predicted uncertainties to enhance the safe operation.

6. Results and deliverables

This project has achieved its main goal of advancing uncertainty-aware and safety-enhanced management strategies for CAVs in mixed traffic environments. Through the development of new modeling techniques, adaptive control frameworks, and data-driven evaluation methods, the project makes significant contributions to the general objectives of the FFI program and particularly to the sub-program on Smart Vehicles and Automation. Below is a structured overview of the project's outcomes and how each deliverable supports the project objectives and FFI's ambitions for safer, more intelligent vehicle systems.

Objective 1: Uncertainty perception and quantification in mixed traffic scenarios

The first objective focuses on enabling CAVs to actively perceive and quantify risk caused by uncertainties such as behavioral unpredictability of human drivers, communication disruption, and insufficient environmental observability. The project produced the following key results under this theme:

(1) Uncertainty-aware HDV trajectory prediction

To model the diverse behaviors of HDVs, a personalized trajectory prediction framework (see Fig. 1), named LSTMMD-DBV (long short-term memory and mixture density networks with driving behavior vectors), was proposed. The model, built on a long short-term memory encoder–decoder combined with mixture density networks, allows for probabilistic prediction of future vehicle positions based on both trajectory history and behavior feature vectors. Driver heterogeneity is encoded through feature representations derived from acceleration patterns, lane preferences, and interaction profiles. Additionally, Shapley Additive Explanations (SHAP) were used to interpret the contribution of individual behavioral features, improving transparency and trust in the decision-making process. The model outperformed several benchmark approaches (GP, standard LSTM, LSTM-MDN) across multiple driving scenarios in terms of prediction accuracy and robustness (see Fig. 2 and Table 1).

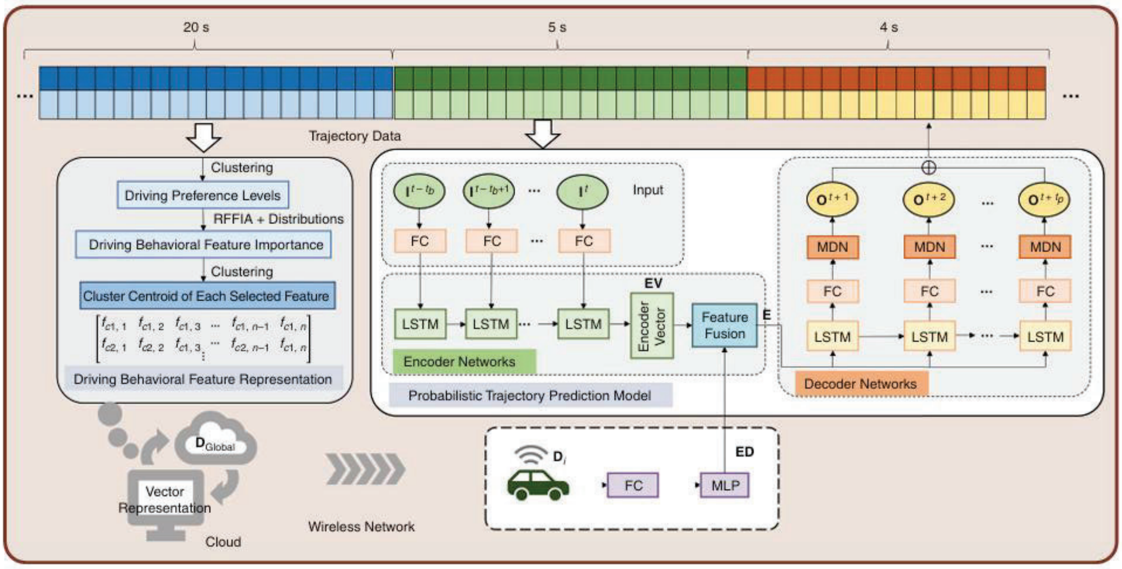
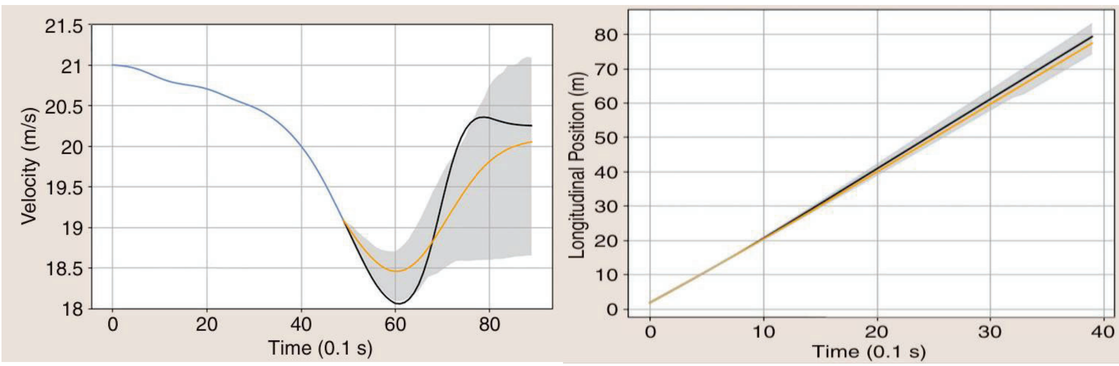


Fig.1 The architecture of trajectory prediction considering driving heterogeneity



(a) Velocity prediction (b) Position prediction

Fig.2 Prediction results

Table 1 A comparison of the velocity prediction results

Model	RMSE (m/s)	RWSE (m/s)
GP	1.339	1.34
LSTM	1.283	1.282
LSTMGM	1.258	1.255
LSTMMD	1.242	1.238
LSTMMD-DP	1.231	1.226
LSTMMD-DBV (proposed model)	1.195	1.189

(2) Communication uncertainty modeling and smoothing

In scenarios with intermittent communication, CAVs may receive delayed or partial information, resulting in discontinuous tracking references (see Fig. 3). This is especially problematic in platooning systems where information propagates bidirectionally. The project introduced a sigmoid-based smoothing function (see Eq. (1)) embedded within a coupled sliding mode controller, designed to minimize transients caused by packet loss while preserving real-time responsiveness. The method was tested under multiple simulated packet loss rates and actuator saturation levels (see Fig. 4). Results confirmed that the smoothed input prevented instability and enabled faster recovery from communication outages, maintaining string stability throughout the platoon.

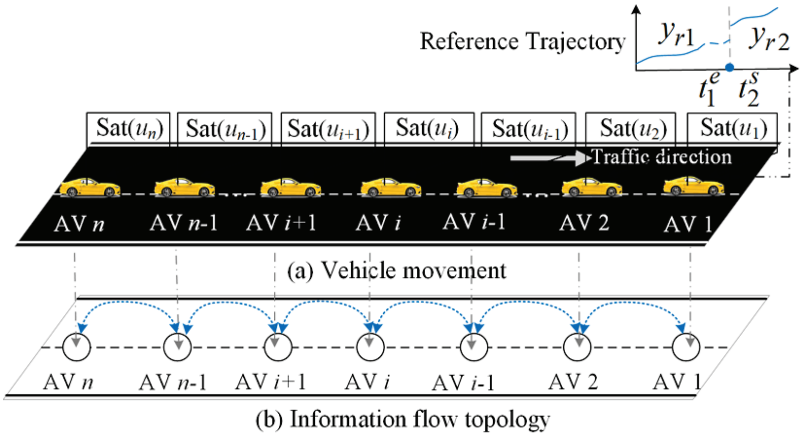


Fig. 3 Platoon trajectory tracking with the discontinuous reference trajectory

$$\varphi(t,t_{sj},t_j^e)=\begin{cases}0, \forall t_j^s \le t < t_{sj} \\ \frac{H_j(t)-\alpha_j(t-t_{sj})-H_j(t_{sj})}{H_j(t_j^e)-\alpha_j(t_j^e-t_{sj})-H_j(t_{sj})}, \forall t_{sj} \le t < t_j^e\end{cases} \quad (1)$$

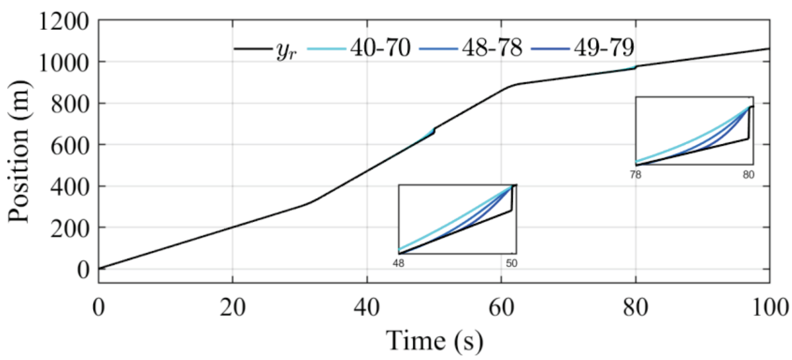


Fig. 4 The smoothed reference trajectory

(3) Risk perception modeling using computer vision

A novel avenue of uncertainty quantification is explored by aligning CAV perception with human perception of traffic safety. We developed a framework for estimating perceived traffic risk in various traffic scenes, encompassing diverse scenarios (see Fig. 5). By employing computer vision techniques, we quantified the information in the images, such as the number of vehicles and their distances. Using a random forest regression model, we built a prediction model to assess risk perception, aiming to distinguish safety between different traffic scenarios. Based on 210 static scenes extracted from the KITTI dataset, over 1900 human subjects provided perceived risk ratings (scale 1-100). Each image was then processed using YOLOv8, identifying key objects (vehicles, pedestrians, signs) without manual bounding boxes (see Fig. 6). A random forest regression model was trained to map visual and spatial features to human-perceived risk. The model achieved an R^2 of

0.59 based on static features alone and 0.74 when vehicle speed was included, demonstrating that even basic perception outputs can be aligned with human safety reasoning.

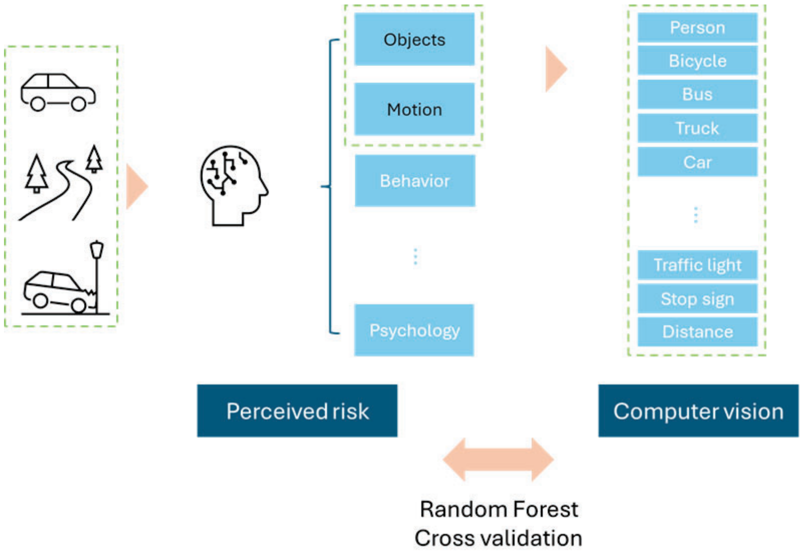


Fig. 5 The framework of risky scenario identification

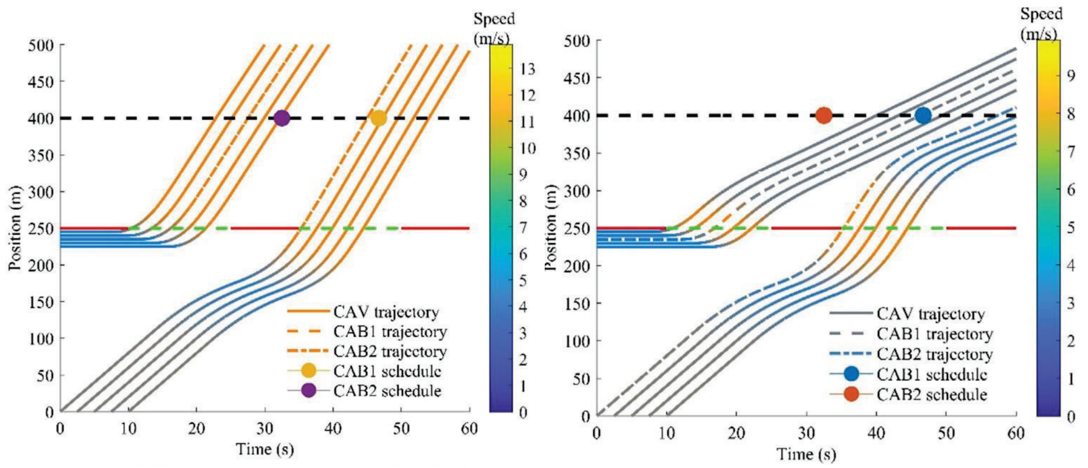
Fig. 6 YOLOv8 identification

Objective 2: Safety-enhanced and uncertainty-aware operational control of CAVs

To address the second objective, the project developed and validated control methods that can respond to perceived risk and adapt to internal/external disturbances in real time. These methods support autonomous operation under uncertainty and ensure safe integration of CAVs into heterogeneous road networks.

(1) Uncertainty-aware trajectory planning and network coordination

To achieve safety and efficiency at the network level, this project developed a signal-vehicle coordination strategy that integrates trajectory planning of CAVs with traffic signal control under uncertain traffic conditions. The method is built upon a MILP model that captures both the binary logic of signal phase transitions and the continuous dynamics of CAV movements. It allows for the optimization of signal states and vehicle trajectories in a unified framework, accounting for fluctuations in traffic demand, variation in vehicle arrival times, and potential perception or communication uncertainty. The model ensures that CAVs can adjust their speed profiles proactively in response to real-time signal plans, enabling smoother flow through intersections and reducing the likelihood of unnecessary stops or harsh braking. At the same time, the signal control adapts dynamically to the predicted arrival patterns of CAVs, maintaining safety margins such as minimum green time, phase conflict avoidance, and downstream saturation protection. This coordination mechanism was tested in a simulated four-arm intersection under different traffic demand levels, CAV penetration rates, and signal cycle configurations. Results show that the method significantly improves the stability of mixed traffic flows, lowers energy consumption by 15.1%, and enhances time reliability by 22.3% compared to baseline fixed-time or uncoordinated strategies (see Fig. 7).



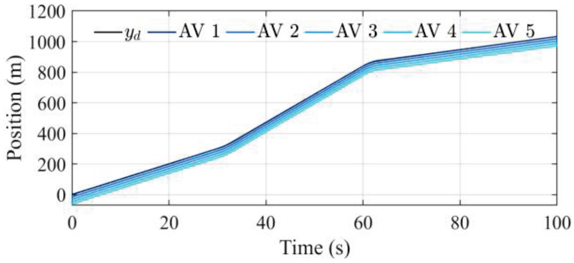
(a) Time-space trajectories with TPS (b) Time-space trajectories with BPS

Fig. 7 Trajectory planning under different control strategies

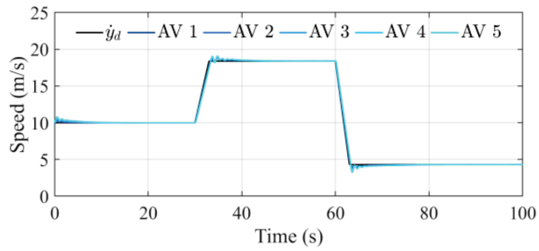
(2) Adaptive control for platoons under uncertainty

To ensure safe and stable longitudinal control of CAVs in platooning scenarios, especially under real-world imperfections such as actuator limitations and degraded communication, the project developed a continuous adaptive control framework tailored for bidirectional vehicle platoons. The control law is formulated within a coupled sliding mode control structure (see Eq. (2)), which enables robust performance under nonlinearities and uncertainty. Key features of the control approach include explicit handling of asymmetric actuator saturation, mitigation of large transient errors caused by trajectory discontinuities, and compensation for non-zero initial spacing errors that are common in mixed traffic initialization. An auxiliary compensator system is embedded to actively adjust control commands when saturation is encountered, ensuring both responsiveness and feasibility of control efforts. The system's stability is theoretically guaranteed through Lyapunov analysis, demonstrating convergence of spacing errors within finite time bounds while preserving inter-vehicle string stability. Simulations conducted in a Carsim-based platform under various communication failure rates, initial condition disturbances, and actuator constraints validate the control design. Compared to baseline controllers such as PID and conventional sliding mode control, the proposed method exhibits significantly faster convergence, improved robustness to packet loss, and smaller steady-state spacing errors (see Fig. 8).

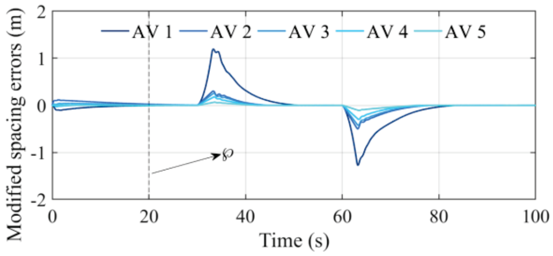
$$u_i = \frac{\omega_i}{\ell_i}\bar{\eta}_i + \hat{g}_i v_i^2 + \hat{h}_i + \mathrm{sign}(\bar{\eta}_i)\hat{K}_i + \varepsilon_i \epsilon_i + \chi_i \epsilon_i^{\frac{r}{p}} + \psi_i \mathrm{sign}(\epsilon_i) - \hat{\vartheta}_i \left(\varepsilon_i \epsilon_i + \chi_i \epsilon_i^{\frac{r}{p}} + \psi_i \mathrm{sign}(\epsilon_i)\right) \tag{2}$$



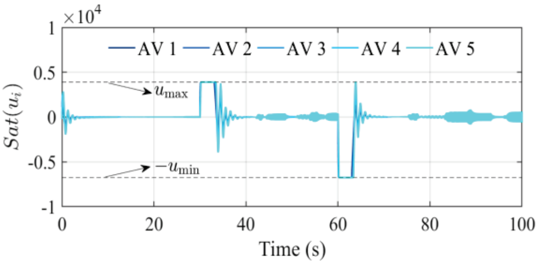
(a) Position tracking trajectories



(b) Speed tracking trajectories



(c) Spacing errors



(d) CAV input

Fig. 8 Trajectory tracking results

(3) Simulation and platform verification

All developed methods were implemented and tested in a high-fidelity simulation environment based on Carsim and MATLAB/Simulink. The simulation platform was extended to include modules for signal coordination, vehicle communication failure, and human driver behavior emulation. Scenario-based testing was conducted to evaluate robustness under: (1) emergency braking or starting, (2) partial or delayed information exchange, (3) Sudden human-driven vehicle maneuvers, and (4) Variable traffic demand and phase timing. Key performance indicators included trajectory tracking accuracy, risk prediction correlation, inter-vehicle spacing stability, and flow energy efficiency. While full experimental validation on test vehicles was limited due to logistical and resource constraints, the simulation outcomes provide strong evidence of practical feasibility.

Deliverables

- A data-driven perception framework for modeling driver behavior uncertainty in mixed traffic;
- A multi-source uncertainty quantification method integrating behavior, communication, and perception risks;
- A continuous adaptive control mechanism for bidirectional CAV platoons under saturation and uncertainty;
- A coordinated signal-vehicle planning algorithm for flow stability under uncertainty;
- Simulation-based iterative testing and verification of perception and control modules under mixed traffic uncertainty.

Contribution to the FFI Program and Subprogram

The outcomes of this project directly contribute to the overarching goals of the FFI program by advancing the scientific and technical foundations for safe and intelligent operation of CAVs in mixed traffic environments. In particular, the project addresses key priorities of the "Smart Vehicles and Automation" subprogram, which seeks to develop autonomous functions that are robust, explainable, and verifiable under real-world conditions. This project contributes in the following specific ways:

- It delivers practically oriented perception algorithms for capturing behavioral uncertainty of HDVs, using interpretable deep learning models and data-driven behavior representations. These models help CAVs better anticipate and adapt to the surrounding traffic context, a critical step toward human-compatible autonomy.
- It introduces a continuous, saturation-aware, adaptive control mechanism for platoons, which preserves safety and stability even in degraded conditions. This supports FFI's emphasis on real-time robustness and safe integration of automation.
- The project bridges vehicle-level and infrastructure-level intelligence by developing a coordinated signal-vehicle planning algorithm. It supports traffic flow stability and energy efficiency through real-time MILP optimization under uncertainty, directly contributing to sustainable traffic automation strategies promoted by the program.
- All methods were tested in a realistically parameterized simulation framework, enabling robust verification and reproducibility-important elements of the FFI agenda on industrial applicability and future testing pathways.

In sum, the project helps move CAV innovation forward by integrating uncertainty awareness, system-level control, and practical testing tools, thereby contributing both technical innovation and methodological maturity to the goals of the FFI program.

Goal Fulfillment and Deviations

The project has fully achieved its original goals as outlined in the proposal, with all five defined deliverables completed and mapped to concrete outputs.

- D1.1 and D1.2 were fulfilled through the development of an interpretable trajectory prediction framework and multi-source uncertainty quantification pipeline. These outputs demonstrated not only technical soundness but also practical relevance through detailed testing and human-labeled validation data.

- D2.1 and D2.2 were realized through advanced control designs for platoons and coordinated vehicle-signal interaction, both under multiple dimensions of uncertainty. These algorithms were tested against state-of-the-art baselines and showed clear performance advantages in energy use, flow stability, and safety margins.
- D3.1 was successfully delivered through a modular CarSim-MATLAB platform supporting iterative testing of both perception and control modules under a wide variety of uncertainty conditions.

Positive deviations from the plan include:

- The introduction of risk perception modeling using computer vision -based labeling, which was not originally planned but adds a novel, human-centered layer to the perception pipeline.
- The use of SHAP-based explainability in trajectory modeling, improving transparency and contributing to the growing demand for interpretable AI in safety-critical systems.

Negative deviations are limited. The originally proposed experimental testing on physical vehicles was constrained due to resource and scheduling limitations. However, this gap was effectively mitigated through high-fidelity simulation in Carsim with parameterized traffic scenarios and system non-idealities. The developed control and planning models remain compatible with real-world deployment in future testing rounds. Overall, the project met or exceeded expectations in all key areas and has laid a solid foundation for future applied research, pilot deployment, and industrial transfer under the FFI ecosystem.

7. Dissemination and publications

7.1 Dissemination

How are the project results planned to be used and disseminated?	Mark with X	Comment
Increase knowledge in the field	X	On September 19, 2024, Kun Gao presented the findings at the SAFER office, discussing the practical impact of CAV platoons on traffic safety and efficiency, while engaging with experts to explore future research directions and applications.
Be passed on to other advanced technological development projects		We plan to apply for new larger project based on the project outcomes for more and advanced technological development with Alkit Communications. The budget the prestudy is not enough for conducting real technological development.
Be passed on to product development projects		
Introduced on the market		
Used in investigations / regulatory / licensing / political decisions		

7.2 Publications

[1] Wang, S. L., Gao, K., Zhang, L.F., Liu, Y., and Chen, L., 2025. Probabilistic prediction of longitudinal trajectory considering driving heterogeneity with interpretability. IEEE Intelligent Transportation Systems Magazine, vol. 17, no. 2, pp. 110-125, 2025.
[2] Wang, L.C., Zhou, Z.Y., and Cui, S.H., 2025. Balancing bus punctuality and heterogeneous flow stability under a connected environment. Automotive Innovation, doi, 10.1007/s42154-024-00338-4.
[3] Cui, S. H., Gao, K., Xue, Y. J., and Yu, B., Adaptive control of bidirectional platoons with actuator saturation and discontinuous trajectory tracking. IEEE Transactions on Intelligent Transportation Systems, (in Second Review).

8. Conclusions and future research

This project has addressed the pressing need for safe and resilient CAV operation in complex mixed traffic environments. By focusing on uncertainty perception, quantification, and adaptive control, the project has delivered a cohesive framework that allows CAVs to navigate unpredictable traffic scenarios with greater awareness and robustness. The key achievements include the development of a trajectory prediction model that incorporates human driver heterogeneity, a multi-source uncertainty quantification method that accounts for communication disruptions and behavioral unpredictability, and an adaptive control framework for platoons operating under actuator saturation and reference discontinuities. In addition, a coordinated signal-vehicle optimization model was introduced to enhance intersection performance under uncertainty, and all methods were validated within a Carsim-based simulation environment reflecting real-world conditions. These contributions align well with the goals of the FFI program and represent meaningful progress in enabling CAV systems to operate reliably in non-ideal environments. The project has also provided a set of algorithmic and simulation tools that can serve as a foundation for future experimentation and development.
Looking ahead, several research directions emerge naturally from the work conducted. First, there is a need to integrate real-time sensor data with the developed perception and uncertainty models. This includes the fusion of camera, LiDAR, and radar data to enable end-to-end deployment on experimental platforms. Second, transitioning from simulation to physical implementation remains a priority. Future work should focus on deploying the proposed control and planning modules on small-scale or full-scale test vehicles to assess performance under real dynamics, system latency, and environmental disturbances. Participating parties and contact persons
This project was conducted through a collaborative effort involving both academic and industrial partners, each contributing complementary expertise in CAV technologies, vehicular communication systems, and simulation-based development. From Chalmers University of Technology, the participating researchers were Kun Gao, Marina Wiemers, and Shaohua Cui, who led the work on uncertainty modeling, control strategy development, and simulation testing. From Alkit Communication AB, Mathias Johanson and Anna Ridderstolpe contributed with their expertise in CAV infrastructure and communication

technologies. Bogdan Diaconu from Fellowbot AB participated in discussions related to future deployment and industrial applicability.