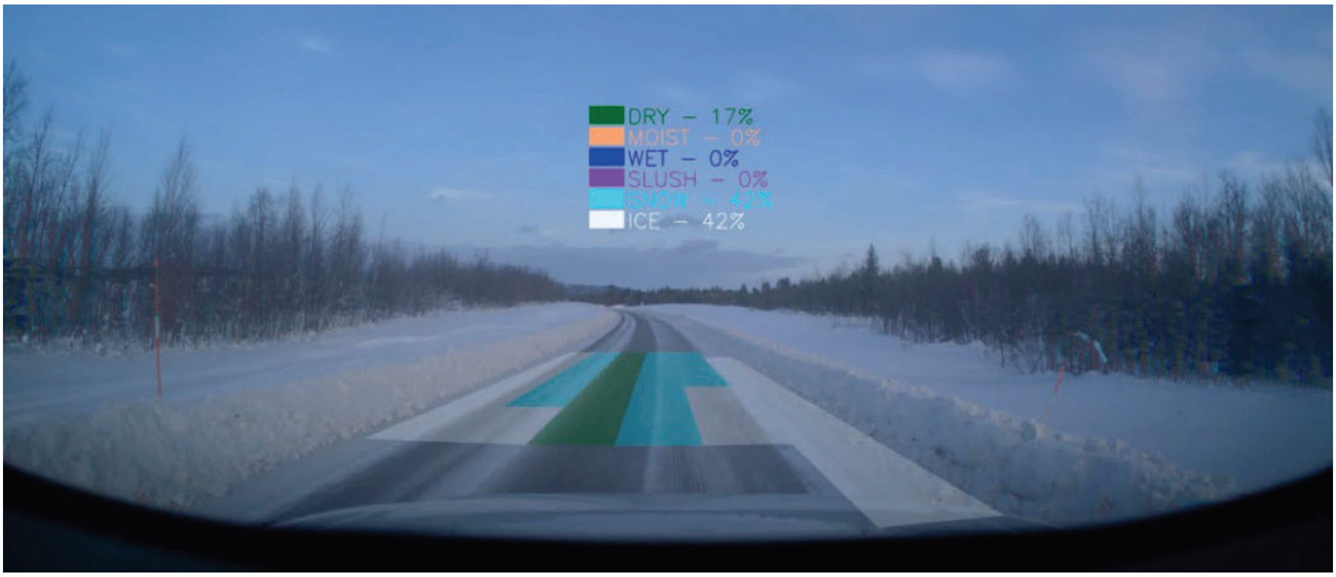
# Vehicle Motion Control Using Data-Driven Varying Road Friction Map

**Public report**




Project within Safe Automated Driving

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FFI

Fordonsstrategisk
Forskning och
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## 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

In summary, the project has developed a pipeline for varying road condition estimation algorithm using different onboard sensors, as well as the potential use cases to improve vehicle motion planning and control at adverse weather conditions.

1. Developed the road weather condition data acquisition and semi-automated annotation method via different sensor modalities (onboard sensors, camera, LIDAR).
2. Explored the data feasibility and quality for the development of friction estimation algorithms.
3. Inferred deep machine learning models to classify the road weather conditions using perception sensors (camera, LIDAR, camera&LIDAR), at both scene, lane, grid and semantic levels.
4. Established optimal control framework for evaluating the friction map performance in different driving scenarios, e.g. uniform and split friction, straight and curved, low and high speeds, longitudinal and lateral maneuvers.
5. Generated friction map quality matrix with criteria based on uncertainty, accuracy, confidence, and availability using the optimal control framework.

Volvo Cars plans to continue the investigation as a form of advanced engineering project with focus on vehicle testing.

# 2. Sammanfattning på svenska

Sammanfattningsvis har projektet utvecklat en arbetsflödesprocess för algoritmer som uppskattar varierande vägförhållanden med hjälp av olika inbyggda sensorer, samt identifierat potentiella användningsfall för att förbättra fordonets rörelseplanering och styrning vid ogynnsamma väderförhållanden.

1. Utvecklat en metod för datainsamling och halvautomatisk annotering av väg- och väderförhållanden via olika sensortyper (inbyggda sensorer, kamera, LIDAR).
2. Undersökt datans användbarhet och kvalitet för utveckling av algoritmer för friktionsuppskattning.
3. Utvecklade djupinlärningsmodeller för att klassificera väg- och väderförhållanden med hjälp av perceptionssensorer (kamera, LIDAR, kamera och LIDAR) på både scen-, körfälts-, rutnäts- och semantisk nivå.
4. Upprättat ett optimalt styrramverk för utvärdering av friktionskartans prestanda i olika körscenarier, t.ex. enhetlig och delad friktion, raka och kurviga sträckor, låga och höga hastigheter, längsgående och tvärgående manövrer.
5. Genererat en kvalitetsmatris för friktionskartan med kriterier baserade på osäkerhet, noggrannhet, tillförlitlighet och tillgänglighet med hjälp av det optimala styrramverket.

Volvo Cars planerar att fortsätta undersökningen som ett avancerat ingenjörsprojekt med fokus på fordonstestning.

# 3. Background

The success of autonomous drive (AD) and next generation advanced driver assistance systems (ADAS) largely depends on active safety sensors for observing the drivable road conditions, to enable accurate decision making and optimal control of braking, acceleration, and steering functionalities. One primary component of drivable environment conditions is the road surface condition that varies largely with inclement weather, ground surface texture-based irregularities, road debris and road administration. One key parameter associated with the tyre grip is the road friction coefficient which become low when snow, ice, water or even just wet leaves is present.
Climate and accident data collected in Sweden from 1993 to 1997 showed that the risk of accidents increase 3-30 times when snow or ice is present compared to dry road. In the US, 24% of all crashes are weather-related and 1,300 people are killed, and more than 116,800 people are injured in vehicle crashes on snowy, slushy or icy pavement annually.

To tackle this safety problem with low friction, Volvo cars have spent more than 15 years of development and research in friction estimation. Participation in the IVSS project gave knowledge to start the development of physical model-based friction estimators using the tyre as a sensor. One major disadvantage is however that the estimator availability is low since the vehicle must either brake, accelerate or turn aggressively to enter the tyre's non-linear region where the friction information is obtained. During normal life driving this type of manoeuvres will not happen frequently. To further increase the estimator ability, contactless and indirect methods have been elaborated using e.g. camera together with machine learning. Using AI-based methods, Volvo Cars have started to focus on more data-driven models to ease the burden of calibration and allow for more precise modelling, with better adaption to each individual vehicle.

# 4. Purpose, research questions and method

To increase both availability and correctness of the road condition estimate, this project aims to fuse manifold sensors such as camera and vehicle dynamics sensors. Since front-looking perception sensors including camera and lidar can provide the possibility to estimate *varying* friction *ahead* the ego vehicle, the development of new algorithms for vehicle motion control functionalities is enabled. The main problem here is road friction uncertainty. When the uncertainty is high, active safety functions risk to act on "low friction false alarm", e.g. warn or intervene too early, which is deemed to be experienced as irritating. On the other hand, with high uncertainty, active safety functions could "miss detection of low friction", which risks leading to accidents because the needed warning or intervention is missing.

The project will give general understanding of varying road friction map on the following questions:
• How does spatial varying friction influence the controllability of a vehicle? That is, if the friction varies in front of the vehicle, in both longitudinal and lateral direction, how does it influence the braking capability and the curve taking?
• How accurate does friction information need to for the feasible application in active safety and autopilot functions?
• How should friction information be represented in a form of quality matrix, confidence and spatial resolution to be useful in active safety and autopilot functions?
• How to improve friction estimation according to the requirements above, by vehicle motion and perception sensor?
• How to generate and update the motion (acceleration, deceleration, steering) capability using the road friction map for tactical motion planning ahead?

This new knowledge will bridge the gap between friction estimation and optimal vehicle motion operation so that the quality measures of friction information become relevant for vehicle control.

For the varying friction map generation, a set of deep learning neural network models will be investigated. For the friction adapted vehicle motion control, model-based approach will be used to optimally tackle the friction map uncertainty and accuracy performance measures.

# 5. Objective

The project aims to explore the algorithms upon which new, or improved, safety functionalities can be based:

- Methods and tools for obtaining spatial friction estimates based on several information sources.
- Algorithms to warn manual drivers approaching road segment, e.g. a curve, with too high speed.
- Algorithms for self-driving vehicles adapting speed and/or path when approaching situations where friction varies, applicable also at other road irregularities such as potholes.
- Simulation environment for the evaluation of friction aware vehicle control functions, by implementing the spatial varying friction map in the novel motion planning and control architecture and functionalities.
- Vehicle prototype to be built to test and verify the friction aware vehicle control functions, for a few future AD/ADAS functions. The prototype will be used to demonstrate the direct benefit from using the AI-based friction estimation &

prediction, in the new/updated motion planning and control algorithms and interfaces.

# 6. Results and deliverables

The project has focused on two major development tracks: 1) generation of varying friction map, 2) define and use the friction map for vehicle motion control in the favour of AD/ADAS functions on slippery roads.

## 6.1 Road Surface Condition (RSC) classification model

The RSC model is firstly developed with Volvo winter expedition dataset. Dataset was automatically annotated for RSC with the optical camera road states and then manually inspected to rectify errors in RSC labels. RSC classes *Dry/Moist, Wet/Water, Slush* and *Snow/Ice* were considered. The proposed ML model could achieve 0.83 as average RSC F1-scores which measures model's accuracy. Average F1-score was increased to 0.87 when full image is fused with the features from grid-cell based model. Work also was done, where road surface condition (*Dry, Wet, Snow* and *Snow Tracks*) can be detected as ego, left adjacent and right adjacent lane, with average F1-score at 0.9. To achieve pixel level resolution in RSC estimation, semantic labelling has been done with 6 classes: *Dry, Wet, Water, Slush, Loose snow* and *Packed snow.* A semantic segmentation model is therefore being developed using (a) vanilla sematic segmentation, (b) multi-task learning of RSC segmentation and (c) multi-task learning with cross connections between two segmentation branches. All the approaches showed similar performance in terms of accuracy and intersection-over-union performance metrics. Grid cell-based image dataset was created by automated annotation using an industrial optical camera installed on Volvo data collection vehicle. Furthermore, uncertainty for the predicted Road Surface Condition (RSC) segmentation estimate is equally important to know as the estimate itself. The uncertainty is therefore investigated in several ways: (i) simple Softmax, (ii) Temperature Scaling (TS), (iii) class-wise TS and (iv) location-wise TS. According to ECE (Expected Calibration Error) and MCE (Maximum Calibration Error) metrices, TS based approach is then identified as the best method for determine the estimate uncertainty.

At the meantime, RSC classification method is further developed to see the importance of using additional information. RSC was initially classified only based on the image region corresponding to the grid cell. This was used as the baseline. In addition (i) air temperature readings, (ii) image ego-lane, (iii) full image and (iv) lidar reflectance information are used. This study revealed that using full image information has the biggest performance improvement from the baseline model.

For the LiDAR point-clouds data, it has shown that the reflectance is following a clear trend from high to low on the different surfaces: dry, snow, ice, slush, wet, which is expected with 1550nm LiDAR specification. However, the dynamic range of the reflectance is limited due to the instance angle between the laser and the road surface, as opposed to the laser with an object in front. Certain remapping and recalibration of the raw sensor signals is expected to improve the model performance.

## 6.2 Friction adapted vehicle motion planning and control

A nonlinear optimization scheme is formulated to maximize brake force while maintaining a straight path on split-friction surface. There real-time ABS brake test data on both high and low friction surfaces were analysed to quantify the uncertainty of friction estimates and hence decision and control. The analysis of this data led to a methodology to reveal the ideal variation of road friction due to the local properties of the pavement. The method is validated in high-fidelity simulation environment where it shows the maximum deceleration is found to be a function of the friction difference between left and right lane. It was also found that at significant friction asymmetry, steering compensation saturates, rendering it impossible to attain maximum braking at each wheel. The vehicle tends to drift to maintain a straight path during braking.

For the friction-based vehicle motion control algorithm development, a closed-loop optimal controller was designed based on the offline optimization results. It was found that at small split friction, the control function can be straightforward where today's anti-lock braking control system combined with optimal steering control is sufficient. However, at large split friction, the high-friction tires require a reduction in braking to prevent excessive vehicle rotation, thereby adding complexity to the optimal control of brake forces and steering angle simultaneously. The benefits of the developed algorithm are when a) friction is known beforehand, and b) at significant friction asymmetry, not all tires should be saturated as a typical ABS would try to.

In addition, the optimization tool CasaDi has been used to investigate the cases where friction varies in front of the vehicle. The resulting trajectories vary depending on the friction and road curvature. More results show that low friction is more detrimental to maximum braking on the inner side of the curve due to the lateral load transfer.

Later, we extend the use case to compute the path leading to the shortest stopping in cases of laterally varying friction. We introduce three varying road profiles and demonstrate the stopping distance improvement of the proposed method in a high-fidelity simulation. Additionally, we found that computationally efficient Particle Model gives sufficiently accurate reference paths for optimal stopping. We show that when the road conditions are not highly varying, knowing the exact road friction coefficient is less important than knowing the road profile—specifically, areas of high and low friction—ahead of the vehicle. Further, surprisingly, it is safer to overestimate friction when friction changes only laterally.

Lastly, a friction-aware speed-control framework is proposed that provides probabilistic braking guarantees on collision avoidance under uncertain road friction conditions. Road friction is modeled as a spatial Gaussian Process (GP) whose nonstationary variance reflects perception confidence, enabling an adaptive representation of friction ahead of the vehicle. Under a Gaussian friction assumption, we derive an analytic one-sided chance constraint that ensures stopping within a prescribed distance at a specified risk level. This chance constraint is incorporated into a spatial-domain model predictive controller (MPC) as a terminal feasibility condition on the distance beyond the prediction horizon, while safety within the horizon is enforced conservatively by constraining acceleration using GP-based lower bounds on available friction. The resulting MPC formulation is computationally efficient and transparent, which facilitates its integration into AEB and ACC functionalities. Validation through 1,000-run Monte Carlo simulations shows that the empirical hit rate (safety-requirement violations) matches the prescribed risk level. The behaviour depends on how friction uncertainty is modelled: with spatially uniform uncertainty the controller is mildly conservative, while spatially varying friction uncertainty yields behaviour close to the nominal risk. Additional ACC scenarios with a snow–ice transition show that hit rates depend strongly on the assumed lead-vehicle friction model (highlighting the need to model lead braking capability correctly), whereas perception quality and occlusion have relatively minor effects.

In sum, the project has contributed to improving the ability to steer and brake vehicles, hence stability and safety. With improved knowledge on how friction influence safe driving, warning systems for crash risk due to high speed can be given more accurately, and brake systems can be more suitably designed. In a long term, also road authorities may use the knowledge to better prioritize and timely plan the maintenance of winter roads. Hence, the project contributes to safer vehicles and safer driving, both manually and autonomously.

Within the project, prototype functions using varying friction information are developed and started to be tested in real vehicles at the next generation Volvo Cars scalable electric car platform. The project will also push the method development for estimation of friction including data-driven techniques and the systems to make friction information available in general. Cloud techniques for sharing friction information will probably continue to develop many years from now, and this project will indicate the usefulness of such shared databases and what friction information should be included in such databases.

# 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 | The gap between the friction estimates and user function |
| Be passed on to other advanced technological development projects | x | Road condition manager function |
| Be passed on to product development projects | | |

| | | |
|---|---|---|
| Introduced on the market | | |
| Used in investigations / regulatory / licensing / political decisions | | |

## 7.2 Publications

1. Ektor Karyotakis, Derong Yang, Mats Jonasson, Jonas Sjöberg, “Experimental Study on Road Friction Variation and Stopping Distance Uncertainty using ABS Braking Data”. Presented in AVEC’22, https://research. chalmers.se/en/publication/534217.
2. Ektor Karyotakis, Mats Jonasson, Derong Yang, Jonas Sjöberg, “Minimizing Stopping Distance on Split Friction via Steering and Individual Wheel Braking Optimization”. In: Huang, W., Ahmadian, M. (eds) Advances in Dynamics of Vehicles on Roads and Tracks III. IAVSD 2023. Lecture Notes in Mechanical Engineering. Springer, Cham. https://doi.org/10.1007/ 978-3-031-66968-2_37.
3. Ektor Karyotakis, Derong Yang, Mats Jonasson, Jonas Sjöberg, “Optimal Braking and Steering Control Under Split Friction on Curved Roads”. Published in Lecture Notes in Mechanical Engineering, 2024, https://doi. org/10.1007/978-3-031-70392-8_85.
4. Karyotakis, E., Jonasson, M., Yang, D., & Sjöberg, J. (2026). Minimum stopping distance on split friction roads via joint control of steering and individual wheel braking. Vehicle System Dynamics, 1–25. https://doi.org/10.1080/00423114.2026.2630033
5. Ektor Karyotakis, Mats Jonasson, Derong Yang, “Trajectory Optimization for Safe Stops with Laterally Varying Road Friction Ahead”. Submitted to IEEE T-ITS, in March 2025.
6. Ektor Karyotakis. Braking Distance Minimization on Roads with Varying Friction. Licentiate Thesis, Chalmers University of Technology, May 2025.
7. Ektor Karyotakis, Derong Yang, Mats Jonasson, Jonas Sjöberg, “Method for determining a braking distance estimate for a vehicle, method for operating a driver assistance system of a vehicle, data processing apparatus and computer program”. Patent granted (EP4342749B1), Nov. 2024.
8. H. Karunasekera and J. Sjöberg, "In Search for Better Road Surface Condition Estimation – Using Non-Road Image Region *," *2024 IEEE Intelligent Vehicles Symposium (IV)*, Jeju Island, Korea, Republic of, 2024, pp. 3205-3211, doi: 10.1109/IV55156.2024.10588760.
9. H. Karunasekera *et al.*, "Varying Road Surface Condition Estimation in Ego and Adjacent Lanes," *2023 IEEE Intelligent Vehicles Symposium (IV)*, Anchorage, AK, USA, 2023, pp. 1-6, doi: 10.1109/IV55152.2023.10186540.
10. Ektor Karyotakis, Nikolce Murgovski, Derong Yang, and Mats Jonasson. ”Friction-Aware Speed Planning with Gaussian Process Uncertainty and Chance-Constrained Model Predictive Control”, submitted to: IEEE Transactions on Intelligent Vehicles, in February 2026.

11. Arun Shenbaga Priyan Vijayan, Derong Yang. Lidar based Road Condition Estimation for Passenger Vehicles. Patent application. Publication number: 20250171028, Nov 2024.
12. Hasith Karunasekera, Derong Yang, Arun Shenbaga Priyan Vijayan, Jonas Sjöberg METHOD FOR DETERMINING A ROAD SURFACE CONDITION, METHOD FOR CONTROLLING A VEHICLE, DATA PROCESSING APPARATUS, VEHICLE, COMPUTER PROGRAM, COMPUTER-READABLE STORAGE MEDIUM, AND METHOD FOR TRAINING A COMBINATION OF ARTIFICIAL NEURAL NETWORKS. Patent application. Publication number: 20250319879, April 2025.
13. Philip Johansson, Viet Le, Arun Shenbaga Priyan Vijayan, Derong Yang, Hasith Karunasekera. ESTIMATING SURFACE CONDITIONS ON A ROAD. Patent application. Publication number: 20240425054, June 2023.
14. Hasith KARUNASEKERA, Derong YANG, Saurabh GAWANDE, Jonas SJÖBERG. ASSOCIATING ENVIRONMENT PERCEPTION DATA WITH DATA INDICATIVE OF A FRICTION CONDITION. Patent application. Publication number: 20240317240, March 2024.
15. Le, Viet. Johansson, Philip, LiDAR-based Road State Estimation, Master's Thesis, 2023-06-22T10:44:15Z. Chalmers University of Technology.
16. Mubina Crnic, Sotiris Koutsoftas. Road Friction Aware Adaptive Cruise Control using Robust Nonlinear Model Predictive Control with Uncertainty Quantification, Master’s Thesis 2025: EENX30. Chalmers University of Technology.
17. Haoqi Yu, Zhe Du. Road Surface Prediction by Camera-based Deep Learning Models, to be submitted Master’s Thesis 2026. Chalmers University of Technology.

# 8. Conclusions and future research

The project has investigated in depth the potential to apply vehicle motion control based on a varying road friction map which is predicted using the perception and motion sensors on board. The method to efficiently collect, curate and annotate the data is established using state-of-art sensor hardware and data analysis tools. A friction-aware longitudinal speed planning algorithm is developed for AEB and ACC that regulates stopping feasibility under uncertain road friction at a prescribed risk level. The quality matrix and performance requirements on the friction map has been generated for both longitudinally and laterally varying friction roads. Future work remains to extend the method and algorithm to more complicated scenarios like curved and hilly roads. Full scale vehicle integration is also planned, based on the promising results obtained so far from the offline data analysis using prototype vehicles.

# 9. Participating parties and contact persons

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