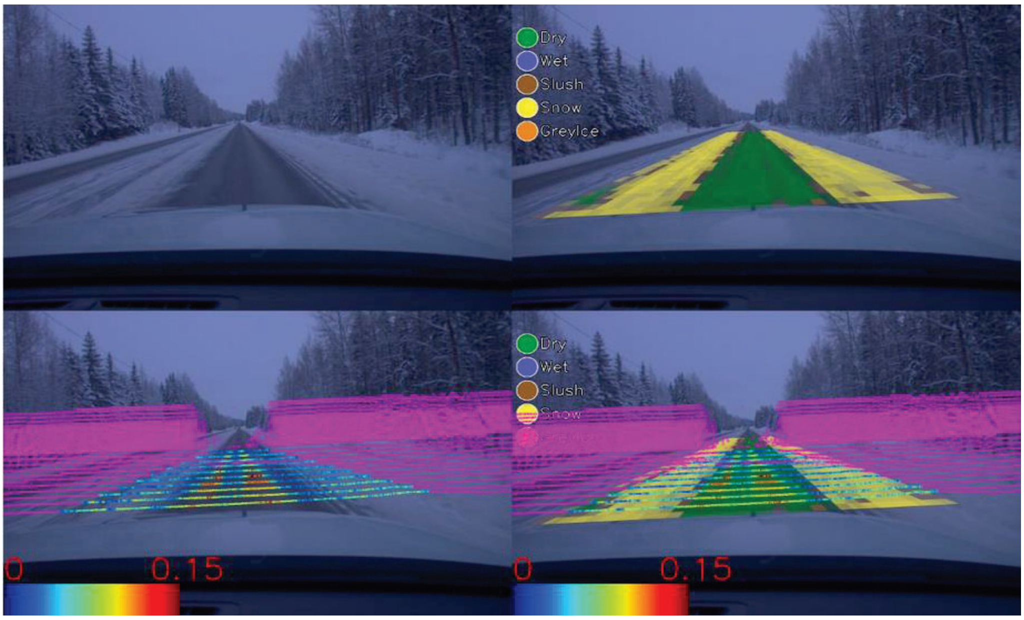
LiDAR-based Road Weather Condition Detection for Increased Traffic safety

Public report



Project with Volvo Car AB and Klimator AB

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FFI 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.

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1. Summary

Slippery roads are a significant cause of accidents for cars. According to the National Highway Traffic Safety Administration (NHTSA), nearly 25% of all car accidents are caused by adverse weather-related factors, such as rain, snow, and ice.

To tackle this safety problem with low friction, Volvo Cars has spent more than 15 years of development and research in friction estimation. Today Volvo Cars has the Road Slippery Alert function in production, which is based on the friction estimate from physical model using the tyre as a sensor. To further increase the estimator ability, contactless and indirect methods have been investigated using e.g. camera and lidar together with machine learning. Using AI-based methods, Volvo Cars have started to focus more on data-driven models to ease the burden of calibration and allow for more precise modelling, with better adaption to each individual vehicle. The preview friction information is also desirable for active safety systems on board to make more diplomatic decision timely.

The focus of this project is on the exploration of the potential of detecting low friction surface condition using the LiDAR on a passenger vehicle. Klimator has been working on the road friction sensing technology for the last decades, where near-infra optical sensor has been developed and verified on different road friction conditions. This optical sensor is expected to have high similarity with an on-board LiDAR sensor e.g. at Volvo Cars. Therefore, Volvo Cars has the interest to perform the forementioned analysis together with Klimator.

As todays LiDAR system on board is optimized for object detection in front of the vehicle. This project does also aim to find a specification for optimal LiDAR setup for passenger cars in road surface condition detection. The end goal is to create more robust active safety systems road weather condition into consideration and decrease the number of accidents that is caused in relation to slippery roads.

Volvo Cars is the main applicant and Klimator will participate as a startup with the aim of adapting LiDAR sensor on board and applying the optical friction sensor as ground truth data.
The project has started in October 2023 and lasted for 1 year now.

Sammanfattning på svenska

Denna rapport syftar till att presentera de senaste undersökningarna om potentialen i att använda LiDAR ombord för att upptäcka vägväderförhållanden. Volvo Cars har funktionen Slippery Road Alert i produktion idag med hjälp av rörelsebaserade sensorer. Nyligen genomförda studier har visat en viss potential för att förbättra prestandan för funktionen med perceptionssensorer som finns ombord nu för tiden. Klimator har arbetat med

vägfriktionsavkänningstekniken under de senaste decennierna, där nära-infra optisk sensor har utvecklats och verifierats på olika vägfriktionsförhållanden. Denna optiska sensor förväntas ha hög likhet med en LiDAR-sensor ombord. Med den extra kunskapen om LiDAR-kapacitet för att förutsäga vägfriktion, kan uppskattningsmetoden smältas samman med andra rörelse- och perceptionssensorer ombord. I slutändan är målet att förbättra tillgängligheten och noggrannheten i klassificeringen av vägväder för säkrare trafiksäkerhet, samt effektivare vägunderhållsarbete. Fältdata samlas in i Volvo Cars datainsamlingsbil som körs i Europa för både sommar- och vinterväglag. Testfordonet är instrumenterat med kamera- och LiDAR-sensorer från Volvo Cars och AHEAD-systemet med två optiska sensorer från marken. Analysen har visat att reflektansen av LiDAR för bilar har en stor potential för att differentiera olika vägväderförhållanden. Detektionens robusthet kommer dock att behöva verifieras med mer data och analys. Möjliga rekommendationer för LiDAR tekniska specifikationer presenteras också i slutet.

2. Background

Road friction information plays a critical role for assuring the safety envelop in autonomous vehicle control systems. The proposed project will contribute to improving further the ability to estimate road friction condition using on-board LiDAR. This is an unknown knowledge gap which has never been explored before, that put this project as a pioneer in this area. The project will push the method development for estimation of friction including data-driven techniques, and to fusion with other perception sensor systems to make friction information available in general. In another aspect, 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 traffic environment.

Klimator AB is a software company with over 30 years of research in applied road climatology. Klimator has two innovations – the data platform Road Condition Data (RCD), providing predictive high precision road weather information, and the sensor fusion solution AHEAD providing real-time detective road weather information. With these innovations, Klimator provides precise and reliable road weather information to the winter maintenance and the automotive industries creating safer roads and enabling scalable autonomous driving (AD) and intelligent driver support systems (ADAS).

As the road friction information will be part of the shared information in the future together with smart route navigation apps, the utilization business model and framework can be easily extended from the results of this proposed project. If the knowledge gained here is promising and useful, we strongly foresee the further opportunities as well as necessity to collaborate with extended actors who might gain benefit with the real-time friction map all over the world. This includes both lidar, map suppliers, as well as data digitalization platform provider, road and traffic authorities. This aligns well with Volvo Cars reputation and vision towards Zero Collisions, by leading in safe vehicle automation.

The application of sensors within the automotive industry is under strong development both when it comes to signal interpretation, development of new functionalities, and the ability of

highly advanced information sharing. These are all technologies that have shown ground-breaking advancements within automotive safety and functionalities such as enhanced collision avoidance systems, autonomous driving capabilities, and overall road safety.
In parallel with the development of sensors, AI has emerged as a game changer in the field of automotive safety and has revolutionized the way of handling data. But due to limited possibilities to add more sensors in combination with the increased cost that follows, the industry must become more creative by utilizing the information that can be extracted from the existing sensors for more than one purpose or functionality. By co-coordinate the sophisticated signals from the existing sensors, with AI and the new abilities of information sharing, the possibility to create new values regarding traffic safety has emerged.

3. Purpose, research questions and method

This Project aims to gain knowledge regarding the potential of utilizing the LiDAR sensor for road weather condition detection. The Project does also aim to propose a specification for optimal LiDAR setup for road weather condition detection in passenger cars.
One Volvo Car test vehicle is to be equipped with Klimator's AHEAD development kits containing two Optical Sensors and one camera. The system will be collecting anonymized data. In parallel, the Test Vehicle collects data from the LiDAR and camera sensors installed on the Volvo Car test platform. The vehicle will be collecting data throughout the Project with a focus on the winter season. Data in the Project will be shared on shared storage, where both Parties may access the data to enable joint data annotation and analysis.

The research questions are hereby:

1. Will the LiDAR sensor on board today be able to indicate different road weather classification? How well is the performance in terms of both accuracy and range?
2. Is there any possible improvement on the LiDAR sensor software specification or data post-processing method to enhance the performance of such classification?

The data to be analyzed are identified as below:

- Volvo Cars LiDAR point cloud in raw format. Each point contains at least information on reflectivity, distance, time stamp, and position.

- Klimator AHEAD optical laser data classifications, GPS data: speed, positions, timestamp.

The test vehicle with the AHEAD optimal sensors at the front bumper side is shown below:


P
Volvo Cars
Data Collection Vehicle
volvocars.com/dcv
UYC 28Y


UYC 28Y

4. Objective

As noted in the application, the objective of this project is to explore:

(1) The potential of utilizing LiDAR sensor for road friction condition detection.
(2) The potential of using applied machine learning methods for LiDAR-based road friction prediction.
(3) The optimal LiDAR orientation and specification for road surface and road weather condition detection.

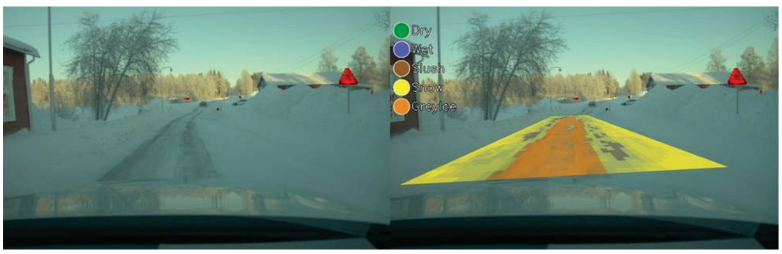
Here the LiDAR orientation has not been studied due to the limited time.

5. Results and deliverables

This chapter presents the result from the analysis based on LiDAR data annotations from Klimator. The optimal sensor and camera image data from AHEAD system were used in the annotation. Here we have investigated the potential of utilizing LiDAR data, also compared to other LiDAR studies in previous research where some recommendations on LiDAR specification are discussed.

5.1 Dataset Overview

We take the example data set in the presentation of analysis here. Some preprocessing of the data is needed to filter out the situations where the LiDAR underperformed. One crucial issue is the absence of points on the road, as shown in the accompanying example image. Despite these constraints, all critical road conditions (dry, wet, slush, snow, etc.) are represented in the dataset.



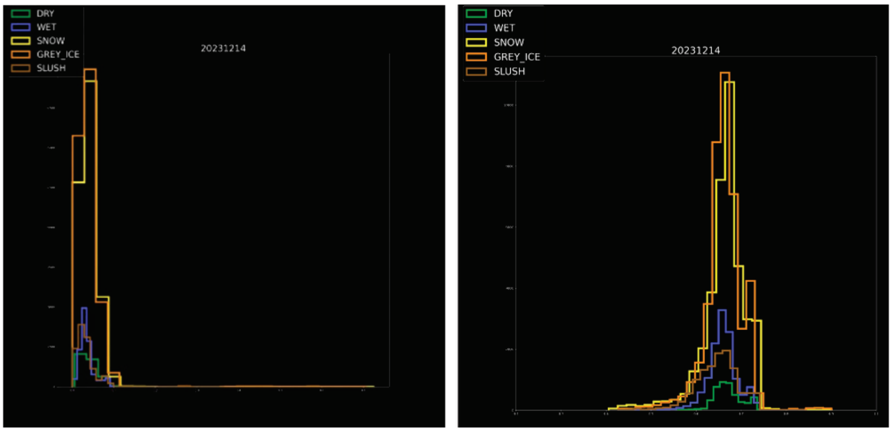
Example of how the Lidar data looks like underperformed. only the road sign and some points are reflected as well as the distribution of the data in the used data set devided into road conditions.

5.2 Reflectance Remapping

Due to the small values for reflectance, Klimator applied the following function to scale up the data:

$$\text{Value} = \left(\frac{reflectance}{2}\right)^{0.1}$$

This "zooms in" on the minute values to make them more distinguishable and analyzable.

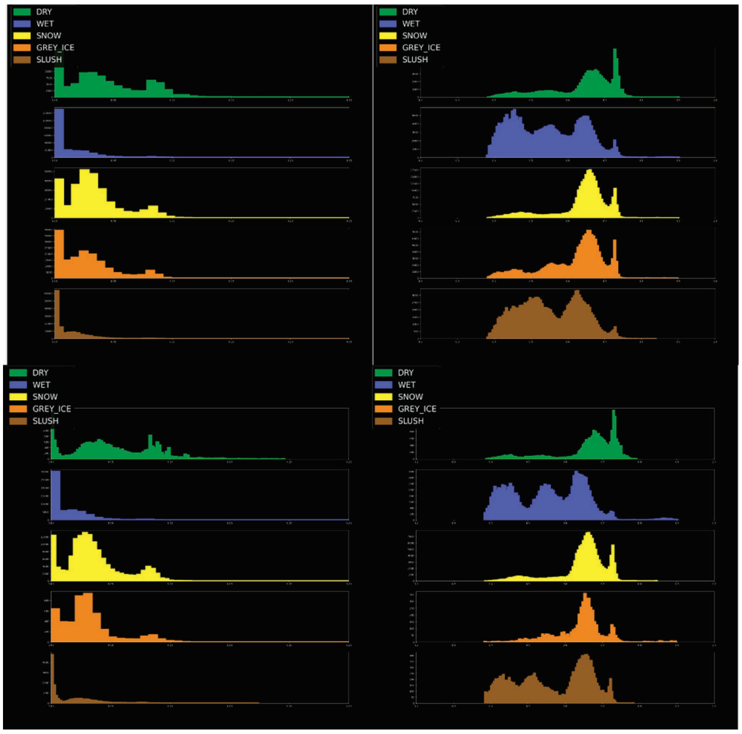


No transformation vs transformed data

5.3 Day-by-Day Reflectance Analysis & Histogram

The daily analysis of reflectance data reveals several key findings:

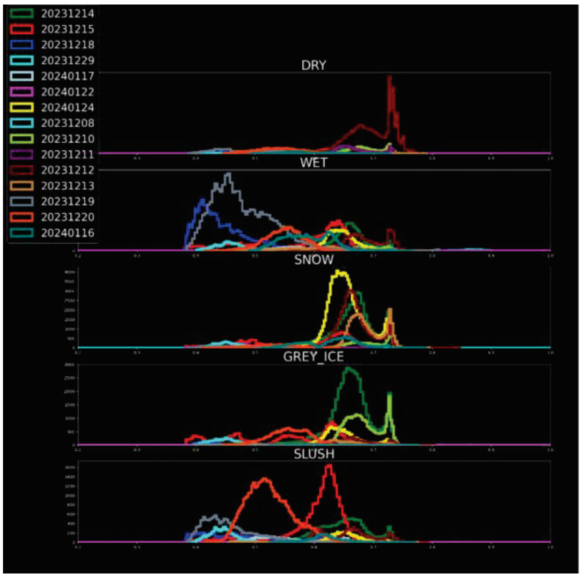
Reflectance Overlap: There is significant overlap in reflectance values across different road conditions. For example, wet and slush surfaces may appear darker, but their values often overlap with other conditions like snow or ice.



Wet and slush sometimes appear darker, but also overlap a lot with other classes

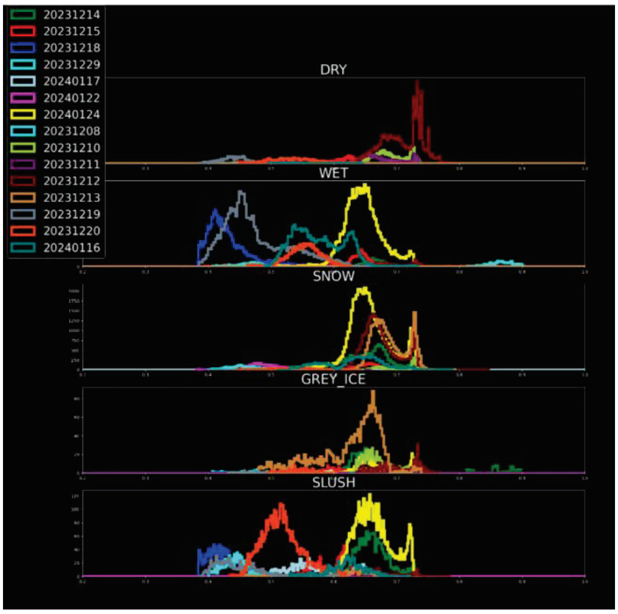
Cluster Center Variation: LiDAR cluster centers, which indicate signal strengths, varied daily, even during identical driving conditions and shown in the figure below. This suggests that there are external factors influencing the LiDAR reflectance. The cause of the variation is unknown at this stage, but could be one of the following:

- Potential power input fluctuations
- Accumulation of dirt or grime on the sensor
- Changes in ambient temperature
- Internal calibration or processing anomalies



The LiDAR cluster centers vary each day, even in the same driving conditions. The different colors represent different days.

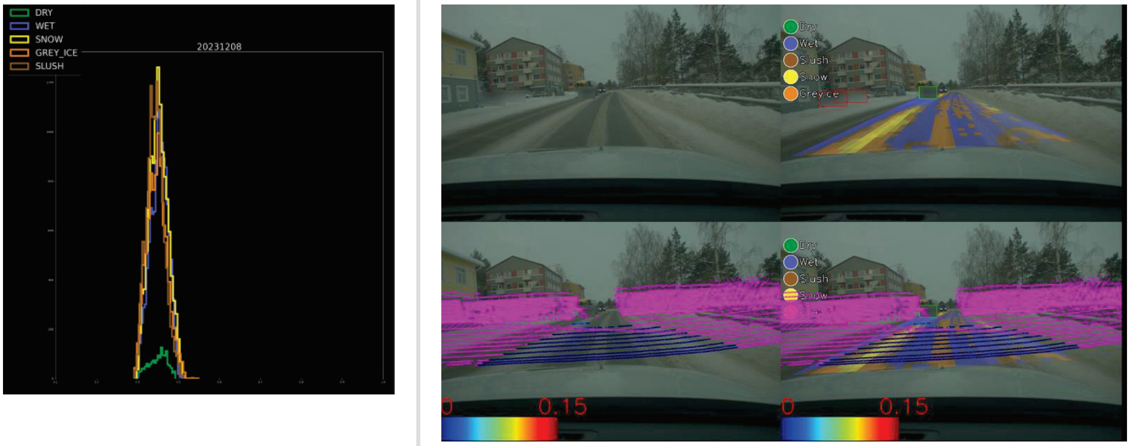
Inconsistent Separation: No reliable or consistent separation exists between road conditions when using the LiDAR's reflectance data. Variations in signal strength make it difficult to clearly distinguish between different conditions. The reflectance range is shown in the graph and table below .



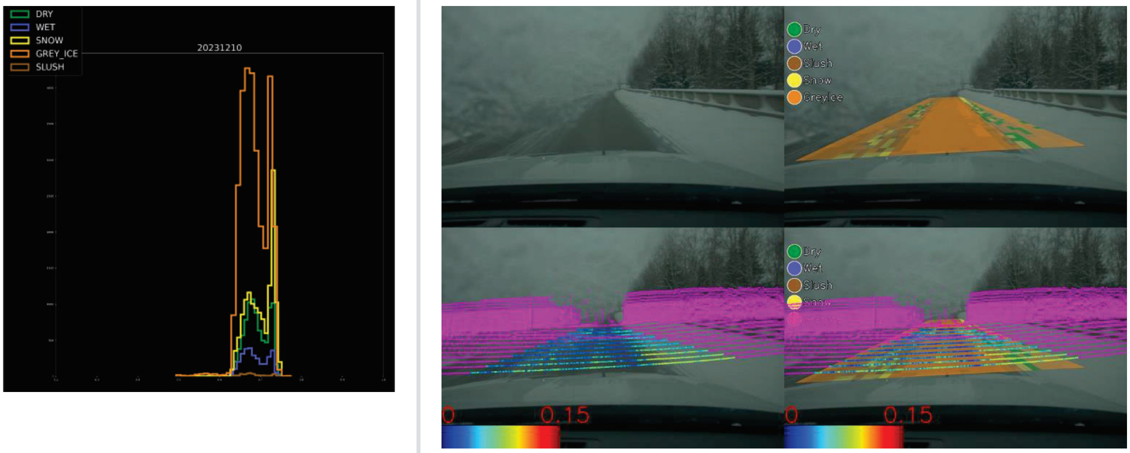
Approximate Reflectance Ranges by Condition:

- Dry: 0.40 - 0.78
- Wet: 0.38 - 0.75
- Snow: 0.40 - 0.75
- Grey Ice: 0.45 - 0.75
- Slush: 0.38 - 0.73

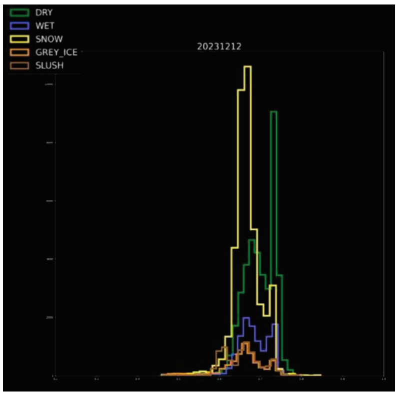
Below, several examples are describing the day-by-day analysis.

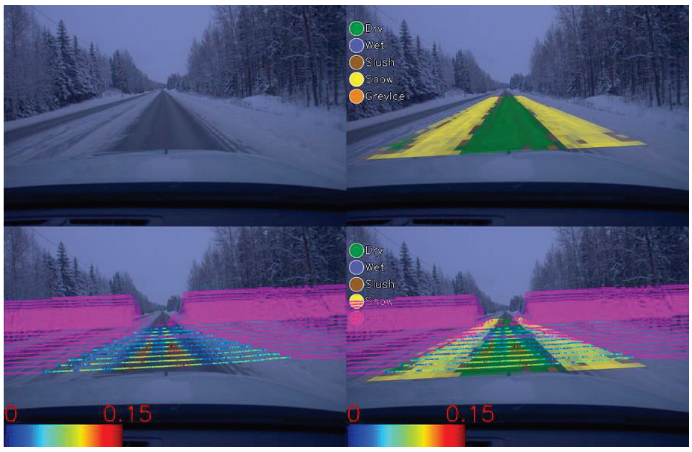


Example 2023-12-08: Varying road conditions, but no separation in the lidar data, even with remapped reflectance

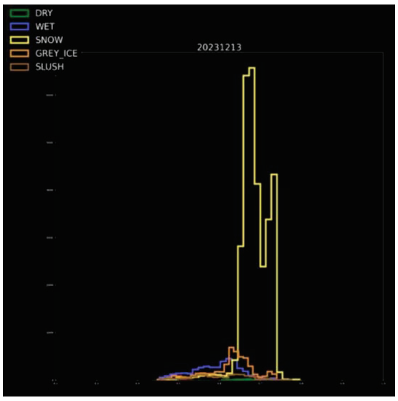


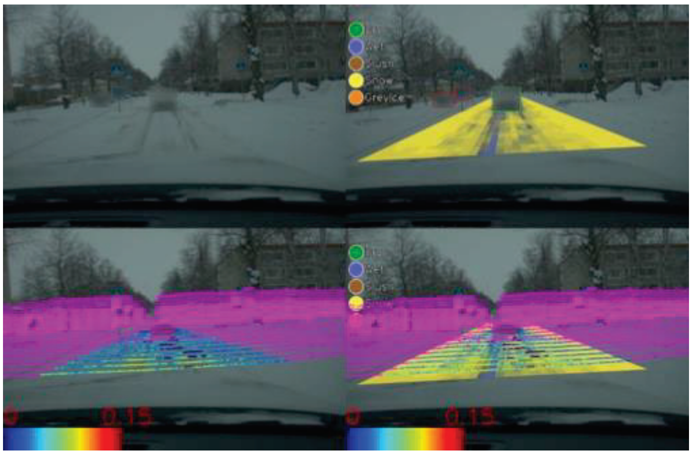
Example 2023-12-10: Promising separation between snow and asphalt, but the higher values on the snow on the right-hand side could be due to a smaller angle of incidence of the Lidar light as the snow bank has a relatively large angle against the road.

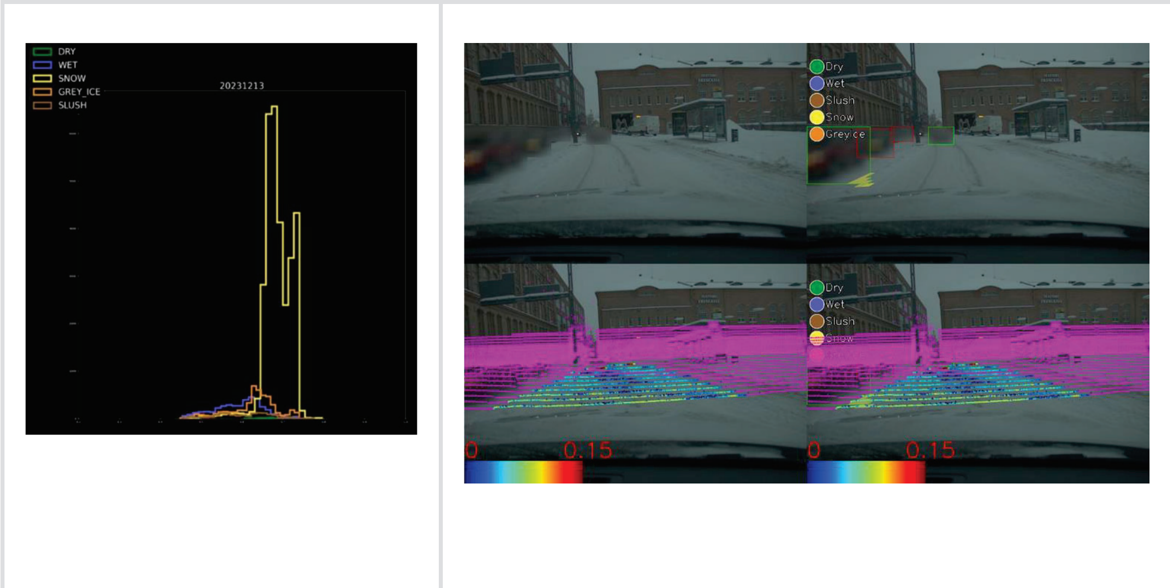




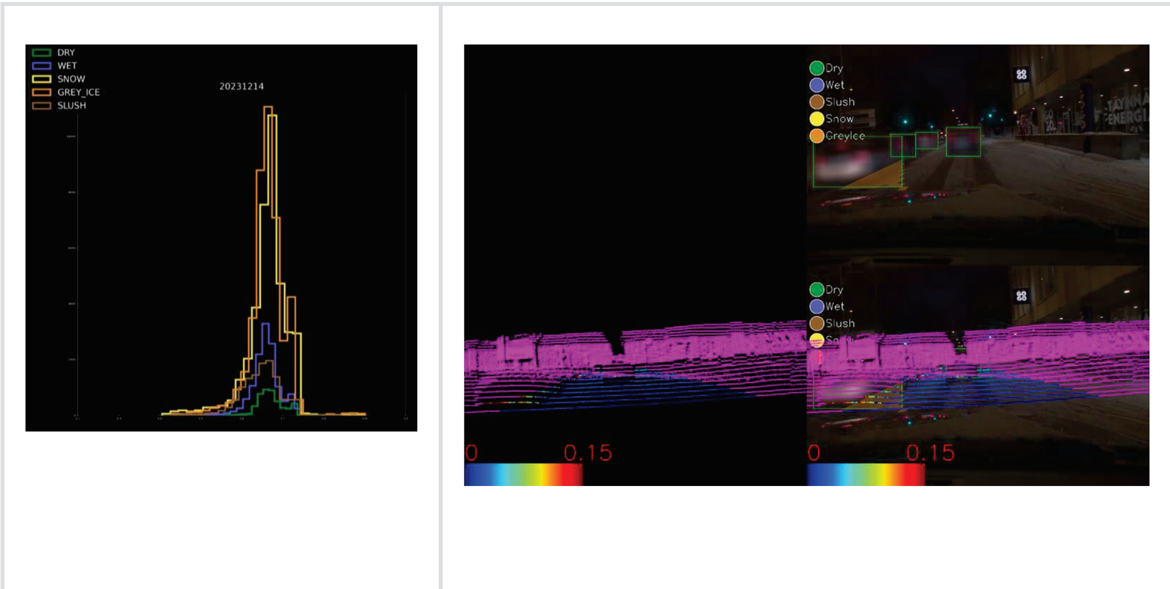
Example 2023-12-12: Promising separation, Dry asphalt appears brighter than the snow







Example 2023-12-13: Mostly snowy, signal is a bit noisy



Example 2023-12-14: Snow with wheel tracks, Minor separation

In summary, due to variations in the signal strength and significant overlaps in reflectance values, no global thresholds can be established for clearly distinguishing road conditions.

5.4 LiDAR Comparison Analysis

To assess if the project's LiDAR sensor has inherent issues, Klimator compared it to another LiDAR utilizing the same wavelength.

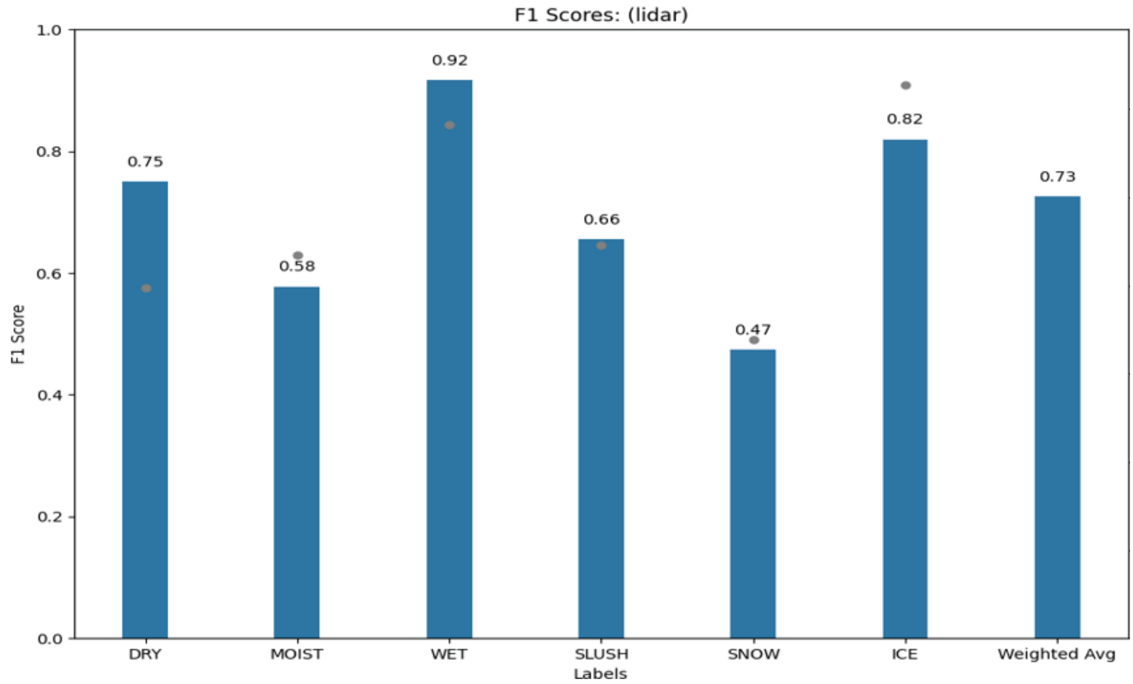
Key results show the other reference LiDAR:

- Higher reflectance values: The reference LiDAR exhibited significantly higher reflectance, likely due to a higher power output. This suggests that the project's LiDAR is operating at lower power output.
- Better separation with more dynamic range: Utilizing a broader dynamic range enabled better class separation of road conditions. Regarding the range, project's LiDAR here uses the normal Lambertian reflectance values as raw signals. That is probably the reason of low dynamic range for road surface reflectance since the instance angle is high compared to an object in front of the car, according to Lambert's Law. Therefore, an up-scaling of the signal value is recommended.

5.5 Preliminary training results

Although the reflectance variation patterns are sometimes not very clear, it is interesting to see how the training network can handle the range of reflectance in a statistical way. Surprisingly, it shows better performance than expected in a preliminary training practice using very simple coevolutionary neural networks.

Below picture shows the F1 score of the six road friction classes and the weighted average accuracy across all the classes. The F1 score is the harmonic mean of the precision and recall. It thus symmetrically represents both precision and recall in one metric. It is interesting to see for dry, wet and ice, LiDAR has higher potential, while worse in moist, snow and slush. This is however understandable, since moist is very difficult to differentiate it with dry, while snow, slush are easily mixed with each other. It is thus expected to achieve better performance if the aforementioned updates on LiDAR specifications can be compromised.



5.6 Main Takeaways

- Varying Signal Strength: There are no fixed thresholds for separating road conditions due to fluctuating signal strength. The cause of this variation remains unclear, possibly related to internal post-processing within the LiDAR sensor that cannot be controlled by any of the project partners.
- Inconsistent Separation: While some days showed potential for separation, others displayed poor separation, especially when the signal strength was weak. On days with stronger signals, separation was somewhat possible, but significant overlap persisted.
- With the current signal strength and variation patterns, machine learning training network shows potential performance. However, improvements is foreseen if LiDAR specifications can be updated for the road surface condition classification, as opposed to today where LiDAR is mainly calibrated for object detection.

The results clearly have contributed to enhance the knowledge of the potential benefits of using LiDAR in road weather condition classification. However, due to more time spent in data collection and post processing including data sharing process set-up, we couldn't investigate yet how the LiDAR orientation and performance thresholds would be optimized. This is certainly a deviation from the expectations in the original application.

6. Dissemination and publications

6.1 Dissemination

How are the project results planned to be used and disseminated?	Mark with X	Comment
Increase knowledge in the field	x	
Be passed on to other advanced technological development projects	x	
Be passed on to product development projects		
Introduced on the market		
Used in investigations / regulatory / licensing / political decisions		

6.2 Publications

One paper is planned to be submitted to "IEEE ITSC 2025, the IEEE International Conference on Intelligent Transportation Systems (ITSC), Gold Coast, Australia."

7. Conclusions and future research

The analysis presents critical insights into the challenges and potential improvements for using LiDAR to classify road conditions. While limitations such as signal strength variability hinder the current analysis, with proper adjustments, the technology may provide more reliable results in the future. Future research can be:

Utilize More of the Dynamic Range: The comparison LiDAR exhibited significantly higher reflectance, possibly due to different signal post-processing. It's possible that the comparison LiDAR performs a remapping of reflectance values internally, similar to what's described in section 1.1, but at a higher bit depth which results in a higher dynamic range.

Investigate and Resolve Signal Variations: Further investigation is required to understand the causes of the varying signal strength, and efforts should be made to resolve this issue.

8. Participating parties and contact persons

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