CAE methodology for vehicle snow packing and sensor availability for active safety and autonomous vehicles

Public report

Project within Traffic Safety and Automated Vehicles - FFI
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FFI in short

FFI is a partnership between the Swedish government and automotive industry for joint funding of research, innovation and development concentrating on Climate & Environment and Safety. FFI has R&D activities worth approx. €100 million per year, of which about €40 is governmental funding.

For more information: www.vinnova.se/ffi

1. Summary

The project was set out to increase the availability of autonomous vehicle functions during harsh weather conditions. These functions are reliant on sensors to read the environment. During harsh weather conditions, contaminants depositing on the car surface such as water spray, dirt, or snow may obstruct the sensor signals and thereby the autonomous software's ability to operate safely. Sensors can be located at a large variety of locations around the vehicle and the quantity of depositing contaminants is dependent on the vehicle design. For these reasons, contamination should be considered when deciding on shape and placement of sensors. In this project we studied snow with the aim of developing a virtual simulation method for snow contamination of cars and to increase the knowledge of how snow contamination occurs.

Mathematical models for the cohesive properties of snow and ice have been developed to predict and understand snow deposition on exterior vehicles surfaces. The models were solved analytically or numerically for ice particle collisions with exterior surfaces. Multiple experimental studies were conducted ranging from small-scale experiments on millimetre-sized single ice particle collisions to large-scale climate wind tunnel experiments on bluff bodies. The cohesive properties of snow were measured using an experimental setup for the angle of repose of snow. A numerical model was proposed for the transport of ice particles in a turbulent flow. In the end, a method that includes the models developed throughout the project was implemented to simulate vehicles driving on snow covered roads.

The project was conducted in the form of a full-time industrial PhD at Volvo Cars with supervision from the department of Chemistry and Chemical Engineering at Chalmers and co-supervision from the division of Fluid and Experimental Mechanics at Luleå University of Technology. The results include a Doctoral thesis, two master's theses, four scientific publications and a virtual simulation method successfully incorporated into Volvo Cars product development.

2. Sammanfattning på svenska

Det här projektet studerar hur snö kan kontaminera exteriöra ytor på en bil. Forskningen motiveras av framsteg inom aktiv säkerhet och utvecklingen mot självkörande bilar. En självkörande bil kan få sina exteriöra ytor nedsmutsade av partiklar vid körning. Dessa partiklar kan vara damm, grus, vatten eller is partiklar ("snö"). När partiklar fastnar på ytor kan dessa påverka prestandan av sensorer eller t.o.m. blockera sensorerna helt. Under vintersäsongen kan snö som faller på marken skapa snötäckta vägar på stora delar av norra halvklotet.

Målet för forskningen har varit att öka förståelsen för vidhäftningsförmågan för snö på exteriöra fordonsytor. Matematiska modeller har utvecklats som innefattar de

huvudsakliga mekanismerna för snöns vidhäftningsförmåga och uppbyggnaden av snö på en yta. Från dessa modeller kan slutsatser dras som är användbara när framtidens bilar ska utvecklas. Experiment på förenklade geometrier visar att snö fastnar och byggs upp på områden där partiklar kolliderar med ytor i låg hastighet och där de aerodynamiska krafterna vid ytorna är låga. Simuleringar av dessa experiment genomfördes och en jämförelse visar att de huvudsakliga mekanismerna för snöuppbyggnad fångas av modellerna

3. Background

Safety systems in vehicles have increased in functionality in recent years, from passive systems, such as airbags and seat belts, into active systems such as brake assistance and collisional avoidance.

This development has led to a reduction in accidents, for example, insurance data reveals that collision avoidance features have reduced rear-end collisions by 37% in Sweden [1]. Advancement within machine learning has accelerated this development and today practically all car manufacturers develop sophisticated cruise control systems with the goal of achieving an autonomous system (self-driving) [2]. A self-driving car will rely on on-board sensors that give input to the autonomous system. Commonly used sensors are radars, cameras, lidars, and ultrasonic sensors. Harsh weather conditions caused by rain, fog or snow can impair the performance of these sensors and potentially cause malfunction of an autonomous system. These phenomena, when the exterior surfaces of a vehicle get soiled by a contaminant, are referred to as surface contamination where the contaminant (snow, water, or dirt) obstructs the sensor by depositing on sensor surfaces. Many studies have previously been conducted regarding water as the surface contaminant, and the topic is then referred to as vehicle soiling or exterior water management [3, 4, 5, 6, 7].

This work is about surface contamination when the contaminant is snow, i.e., snow contamination. Winter season causes snowy roads in large areas of the Northern Hemisphere, where snow covers up to half of this hemisphere in midwinter [8]. Over 70 % of the US population lives in areas with annual snowfall of more than 5 inches (13 cm) [9] and snowy roads account for 24% of all weather-related vehicle crashes in US [9]. Approximately half of the population in Europe lives in areas with yearly snow cover in January, and all regions in Sweden get annual snow. Many drivers can therefore be affected by snow contamination when it causes malfunction of safety systems. Annual winter weather reduces visibility and decreases pavement friction, which increases the likelihood of vehicle accidents. Snowy roads can therefore cause situations where active safety systems for vehicles driving on these roads are less available precisely when they are needed the most. As an example, Jokela et al. [10] tested various lidars, and all sensors in question malfunctioned during the snow tests [10]. Despite these challenges, only few experimental [11, 12] and numerical [13, 14] studies have been conducted regarding snow contamination on vehicles, and most studies have been conducted in recent years. There is especially a gap regarding the understanding of how and where snow is expected to accumulate when driving on a snow-covered road.

The phenomena of snow contamination when driving on winter roads can be divided into three types of driving scenarios: self-contamination, third-party contamination, and precipitation contamination. Self-contamination is occurring when the driving car lifts snow from the ground via the tires and the vehicle is then contaminating itself. This type of contamination is always present if there is a sufficiently thick snow layer on the road. Third-party contamination occurs when the car of interest is driving in a snow cloud generated by another vehicle in front of the vehicle, and this type of contamination is then in practice always present together with self-contamination. The scenario is typically worse when the frontal area of the third-party vehicle is large, for example, a truck, since the aerodynamic wake behind it then will be large which is directly related to the generated snow cloud. Precipitation contamination is referred to the scenario when a car is driven during snowfall and often occurs together with self-contamination.

The intention of this research has been to predict when snow will adhere and accumulate on exterior surfaces. However, the increased understanding of the underlying transport phenomenon is also expected to aid in the understanding of how accumulation of snow can be avoided. The results of this work were intended to be general, enabling it to be applied to any situation where adhesive particles adhere and accumulate on surfaces.

4. Purpose, research questions and method

The project purpose is to increase the availability of autonomous vehicle functions during harsh weather conditions by contributing to the understanding of snow contamination of cars. This is to be achieved by addressing the following research question:

- How are the cohesive properties of snow dependent on properties such as temperature, particle size, etc.?
- How can the collisions of ice particles be described and how does the material properties effect the adhesive loss in a collision?
- How can ice particle-wall collisions be computationally modelled?
- How is snow contamination of aerodynamically bluff bodies dependent on the shape of the body and the properties of its environment such and wind speed and temperature?
- What models are required to setup a complete computational model for snow contamination of cars?

The project consists of seven work packages:

- <u>Literature review, facility, and methodology design (WP1)</u>
  The first work package (WP) will explore the current state of research within the field and summarize the complete set of operating conditions of interest for the project. It also includes design of laboratory scale tests and planning of tasks for the other work packages.
- <u>Investigate wide range of snow types (WP2)</u>
  Knowledge of a wide range of different snow types should be established. The adhesive behavior of different snow types and properties of packed snow agglomerates should be investigated and described.
- <u>Investigate the effects of different surface properties (i.e., hydrophobicity) (WP3)</u>
  Detailed experimental investigations of different surface properties and their effect on snow adhesion should be conducted. Knowledge should be built up and be implemented into numerical models.
- <u>Implement of snow packing results into CFD model (WP4)</u>
  Sub-models and findings should be implemented into a complete vehicle contamination CFD model.
- <u>Implement contamination results into radar/sensor propagation model (WP5)</u>
  The disturbances caused by contamination on signal performance should be implemented into sensor models. (This WP was not completed due to inadequate methods and down prioritization)
- <u>Experimental expeditions (i.e., winter test tracks, real roads, laboratory scale, indoor test facilities) (WP6)</u>

Throughout the project and all work packages, experimental tests and validations will be conducted. Tests will be performed in cooling chambers, wind tunnels, on test tracks and on public roads.

- Project management, reporting and dissemination (WP7)
  Dissemination of the results is done as: a PhD Thesis, Master Theses, publications in scientific journals and presentations at conferences.

5. Objectives

The main goal of the project is to build knowledge about snow contamination of cars. Specifically focusing on sensor blockage caused by contamination and development of simulation methods to predict and prevent it.

At project start, the intent was to develop models that could predict snow adhesion on sensor surfaces including the effect of contamination on signal performance. The effect on signal performance was later excluded from the project objectives due to inadequate methods and prioritization of other project components.

Fulfilling the project main goal will contribute to FFIs high-level objective to reduce the number of injured and killed in traffic by enabling knowledge-based placement and design of sensors that prevents failure of active safety and other autonomous functions due to harsh weather conditions. Contributions will also be made to increasing the global competitiveness of the Swedish automotive industry. With increased product complexity and the intention to shorten lead-times, virtual development will play an increasingly important role in product development. To complement and potentially replace experimental tests, a thorough understanding of the vehicle environment and a way to model it needs to be established. Reliable numerical contamination models will reduce the risk for limited functionality and a decreased customer experience in harsh weather conditions.

For the program *Traffic Safety and Automated Vehicles*, the contribution will primarily be to program area *A – Analysis, Knowledge, and Enabling Technology*. The simulation methods developed in this project are important components in the construction of virtual environments for testing, verification, and validation of autonomous vehicle functions. The autonomous functions need to be tested in realistic user environments which includes contamination and its effect on the vehicle sensors. The project also contributes to program area *F – Automated vehicles in the transport system.* To maximize the benefits of autonomous vehicles it is important that the transport system is functional in all weather conditions and a thorough understanding of how the sensors are affected by the weather is therefore necessary. With increased knowledge in the transport phenomena and mechanisms for the snow contamination of cars, future autonomous vehicles can be design such that the function also in more harsh weather conditions such as winter road conditions.

6. Results and deliverables

The results in this project were published in three journal articles, one conference proceeding, two master thesis projects, one extended abstract to an international conference and a blog post. The main part of the research project was executed by a doctoral student that that in the project also successfully defended a licentiate thesis and a doctoral thesis. This project was divided into six different work packages where all packages were successfully executed except WP5 since sensor propagation models were found to be too immature in order to be combined with contamination results from this work. Therefore, this work package was down prioritized in order to secure the other work packages. Work package WP1 was executed constantly throughout the research project.

The results in this project can be divided into three categories: Ice particle-wall collisions, cohesive properties of snow, and snow contamination in a turbulent flow. These categories will now briefly be summarized, and the readers are referred to the relevant publications for further information.

Ice-particle collisions with walls were studied to comprehensively understand the onset of snow accumulation and to predict when snow is likely to stick. This was done as part of WP3 and was needed for WP4. First a numerical model was developed that was presented as an extended abstract at the International Conference Multiphase Flows 2019 (ICFM). Based on the feedback from the scientific community the model was further developed and later published as a journal paper in Powder Technology [15]. The topic was further studied experimentally in an indoor test facility where the energy losses of ice particle-wall collisions were measured. A regime map for ice particles colliding with massive walls at low and high velocity were formulated based on those experimental results as well as the previous published numerical model. The regime map as well as the experimental method and results were published in Powder Technology [16]. An illustration for the regime map is shown in Figure 1 where the coefficient of restitution e_n is plotted as a function of impact velocity for a millimetre-sized ice particle. The results contribute to the objectives of the FFI-program by supplying numerical tools that can be used in vehicle development to enhance the sensor availability on future autonomous vehicles.

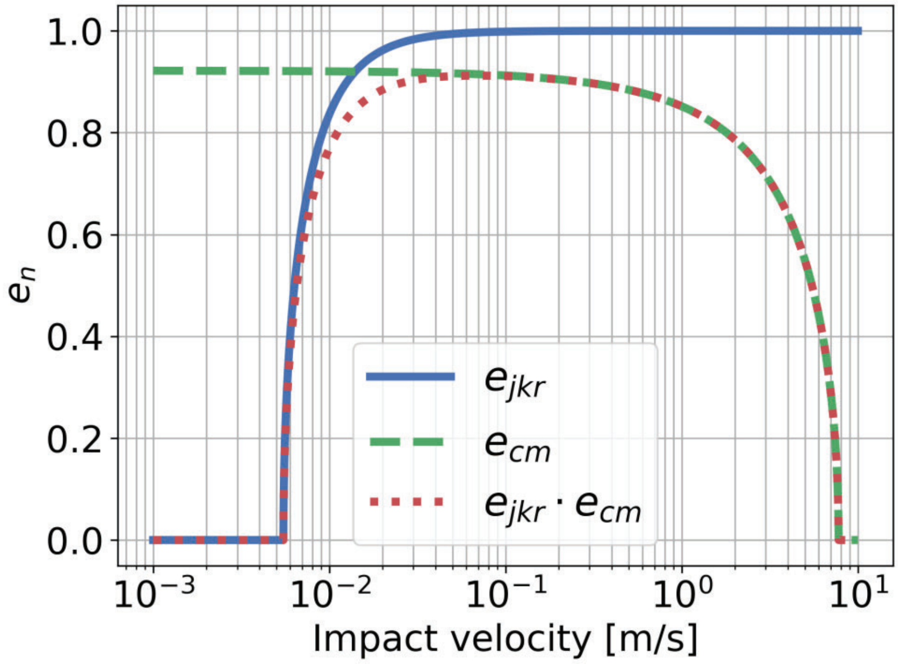

Figure 1 The coefficient of restitution e_n for ice particles colliding with massive walls with $D_p = 1\ mm$ at $T = -12\ °C$. Blue solid line shows e_n for the JKR model e_{jkr}, and green dashed line shows e_n for the collisional melting model e_{cm}. Dotted red line shows the combined e_n by taking the product of the contributions.

The cohesive properties of snow were studied by experimentally measuring the angle of repose of snow. This is a commonly used measurement technique for granular materials that is often used as a validation approach when simulating such materials. Measurements of the angle of repose of snow were performed throughout the research project where multiple different snow samples were collected and classified according to the International Classification of Seasonal Snow on the Ground [17] before the measurements. The angle of repose of snow is depicted in Figure 2 together with some of the main findings that was published as a journal paper in Cold Regions Science and Technology [18]. The results show that the cohesive properties of snow increase with either a decrease in grain size, a lowering of fall height or an increase in temperature. Based on the classifications of the different snow samples, a deeper knowledge of snow properties was obtained that is valuable for the research topic. Significant differences between the snow sticking on a vehicle (subset of smaller particles) as compared to the snow present on the ground, were found. The angle of repose of snow study was done as part of WP2.

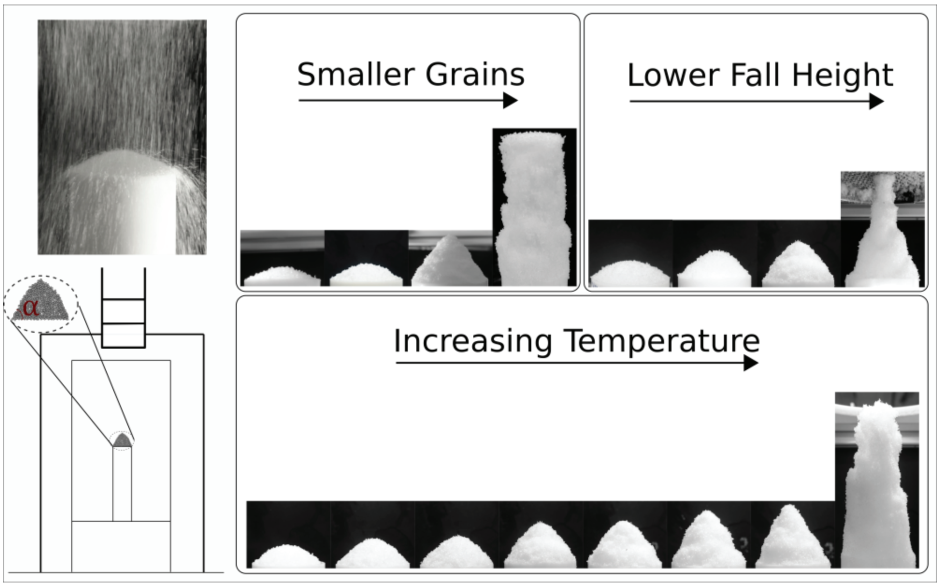

Figure 2 - Illustration of the angle of repose of snow as well as a summary of the core findings of the study.

The angle of repose of snow was also studied numerically using the Discrete Element Method (DEM) in a master thesis project where it was found that the temperature dependency could be modelled using the material parameter work of adhesion. The results were published in the master thesis as well as in a written blog post in collaboration with the software vendor Altair EDEM [19].

The two mentioned categories above quantified collisional properties of single ice particles as well as cohesive properties of multiple ice particles (snow). When a vehicle is driven on a snow-covered road, the turbulent air flow is the main transportation mechanism for the present snow (ice particles). To study the effects of turbulence, the snow contamination of two simplified bluff bodies were studied as part of WP4 where a wedge geometry and the Ahmed body [20] were studied. A master thesis project was conducted where an experimental study was carried out using the climatic wind tunnel at Volvo Cars and numerical methods were tested to reproduce the experiments. Further research was conducted after this master thesis which then led to the development of a complete numerical framework for the snow contamination of bluff bodies that replicate obtained experimental results. The framework is using Computational Fluid Dynamics (CFD) to couple a turbulent air flow with adhesive ice particles. An adhesion model was developed within the framework based on the previous studies for ice particle collisions with walls to predict where snow is likely to stick and accumulate on a bluff body. The framework also includes a resuspension model to predict where aerodynamic forces can shear away snow at surfaces. With the framework, simulations were performed on the bluff bodies that replicate the experiments in the wind tunnel. The comparison showed that the most important characteristics of the snow contamination on the bluff bodies were captured in the simulations. An example of such a comparison is shown in Figure 3 which shows left side surfaces of both the studied Ahmed body as well as the wedge geometry. The results of the study were published as a conference proceeding at WCX SAE World Congress Experience [21] where the material was also presented both using a virtual presentation and a presentation on-site. The publication was chosen among the top contributions at the conference and was therefore chosen to be republished as a journal article.

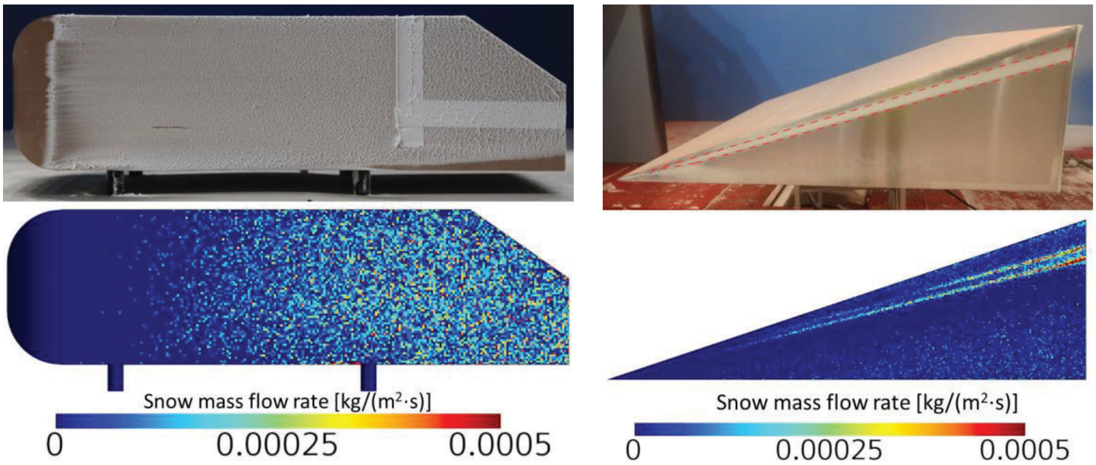

Figure 3: Deposited snow on the side surfaces of each bluff body. Top figures show the wind tunnel results including dashed red lines that highlight regions of increased snow deposition and bottom figures shows the snow mass flow rate from the numerical simulations. Figures to the left show left side surface of the Ahmed body and figures to the right show left side surface of the wedge.

Apart from the mentioned publications numerous experimental trials were also performed to measure the work of adhesion of small ice particles using an adhesion cell developed in a previous research project. This was done to further increase the knowledge with respect to WP2. However, after a calibration study, the measurement equipment was found to be too unreliable for this type of measurements. Similarly different experimental techniques were tested to measure differences between materials of different surface coatings (WP3); however, none were found to be delivery satisfactory results where only small differences were obtained with different surface coatings. A literature study of how ice adhesion is affected by different surface properties also revealed that this is still an unsolved research topic and future fundamental research is needed to understand how material properties are affecting the ice/snow adhesion.

Expeditions to winter test track were done annually in the project as part of WP6. This led to an increased understanding of the research topic where experience from these tests lead to the development of the angle of repose methodology as well as the idea of using simplified bluff bodies. Multiple observations on how the snow contamination of cars depend on temperature, snow properties as well as driving speed were concluded from this field tests. An example of such observations is shown in Figure 4, which shows the snow accumulation on the test track for a vehicle driven 25 km at varying velocities. For further details the reader is referred to the doctoral thesis published in the project [22].

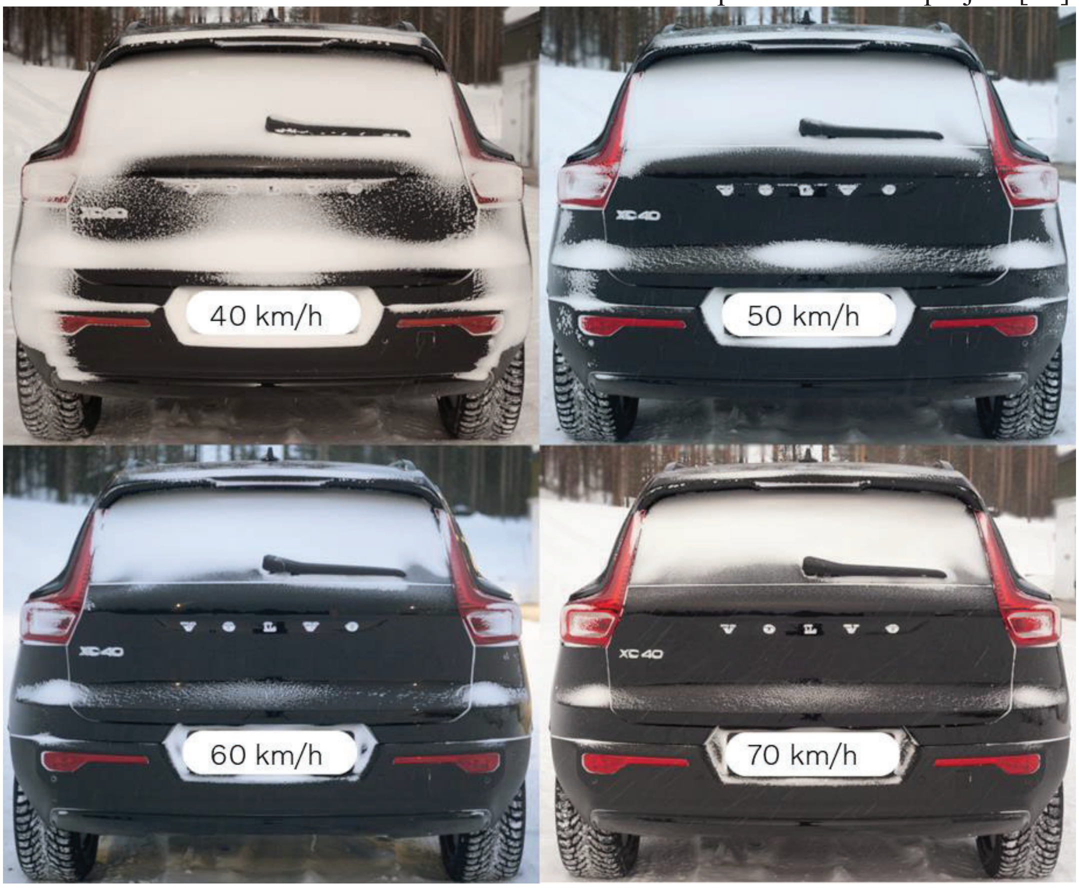

Figure 4: Snow accumulation at a rear view of an electric SUV after driving for 25 km at varying driving speeds.

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 project result has been published in several scientific journals.
Be passed on to other advanced technological development projects	x	A follow-up project, focusing on other contaminants than snow is currently being discussed.
Be passed on to product development projects	x	The results are being used by simulation software developers for validation of their tools.
Introduced on the market	x	The developed simulation methods are currently in use for product development at Volvo Cars. The knowledge gained has also been valuable in the construction of a new climatic wind tunnel at Volvo Cars.
Used in investigations / regulatory / licensing / political decisions		

7.2 Publications

Eidevåg T, Abrahamsson P, Eng M, de Martín L, Rasmuson A. (2019). Adhesion of single and agglomerated snow particles after normal impact with flat surfaces. International Conferences in Multiphase Flows 2019.

Eidevåg, T., Abrahamsson, P., Eng, M., & Rasmuson, A. (2019). Modeling of dry snow adhesion during normal impact with surfaces. *Powder Technology*, *361*, 1081–1092. https://doi.org/10.1016/j.powtec.2019.10.085

Eidevåg, T., Thomson, E. S., Sollén, S., Casselgren, J., & Rasmuson, A. (2021). Collisional damping of spherical ice particles. *Powder Technology*, *383*, 318–327. https://doi.org/10.1016/j.powtec.2021.01.025

Eidevåg, T., Thomson, E. S., Kallin, D., Casselgren, J., & Rasmuson, A. (2022). Angle of repose of snow: An experimental study on cohesive properties. *Cold Regions Science and Technology*, *194*(December 2021), 103470. https://doi.org/10.1016/j.coldregions.2021.103470

Bahaloo, H., Eidevåg, T., Gren, P., Casselgren, J., Forsberg, F., Abrahamsson, P., & Sjödahl, M. (2022). Ice sintering: Dependence of sintering force on temperature, load, duration, and particle size. *Journal of Applied Physics*, *131*(2), 025109. https://doi.org/10.1063/5.0073824

Eidevåg, T., Eng, M., Kallin, D., Casselgren, J., Bharadhwaj, Y., Bangalore Narahari, T. S., & Rasmuson, A. (2022). Snow Contamination of Simplified Automotive Bluff Bodies: A Comparison Between Wind Tunnel Experiments and Numerical Modeling. *SAE Technical Paper Series*, *1*, 1–15. https://doi.org/10.4271/2022-01-0901

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Eidevåg, T. (2022) Snow Contamination of Cars: Adhesive Particle Collisions with Exterior Surfaces, Doctoral Thesis, Chalmers University of Technology. https://research.chalmers.se/en/publication/530277
Tanneru, Y. S. A. I. (2020). *Snow Contamination on Cars*, Master thesis, Chalmers University of Technology. https://odr.chalmers.se/handle/20.500.12380/301424
Bangalore Narahari, T. S., & Bharadhwaj, Y. (2021). *Snow modeling to predict surface contamination of cars,* Master thesis, Chalmers University of Technology. https://odr.chalmers.se/handle/20.500.12380/303895

8. Conclusions and future research

The purpose of the research project was to increase the availability of autonomous vehicle functions during harsh weather conditions by contributing to the understanding of snow contamination of cars. This was done by addressing five different research questions and as a result of this project four scientific research publications were made that addressed these questions. The project also resulted in a licentiate thesis, three master thesis projects as well as a doctorial thesis that was successfully defended.

The conducted scientific studies have led to an increased understanding of how snow accumulates on exterior vehicle surfaces. The studies consisted of experiments and modelling of the details in ice particle-wall collisions, experimental results on the cohesive properties of snow as well as full scale wind tunnel experiments on the snow contamination of bluff bodies. The obtained knowledge is valuable both when designing future experimental procedures and tests to assert the snow contamination on a car but also when performing numerical simulations. With the complete numerical framework, future car designs can be tested in a numerical environment where the snow accumulation can be predicted. With further development the numerical framework can be extended to include not only different types of snow but also the cohesive changes of snow as a function of temperature.

The results from the scientific studies showed that the particle properties in a snow sample have significant effects on both the cohesive properties of the snow as well as the resulting snow contamination on bluff bodies. This is especially important for the machine-made snow, where the used snow cannon in the research project was shown to produce artificially fine snow. Therefore, it is of interest for future research to work on the development of machine-made snow. Fundamental research can be conducted with regards to increasing the understanding of how ice nucleation and how this can be triggered for larger droplets, which should result in larger ice particles. Also, more applied research can be conducted with respect to testing different snow cannons and nozzle properties to manufacture more realistic snow.

The conclusions from this project can also be applied for other sources of contaminants of cars. It is therefore of great interest as future research projects to apply the gained knowledge obtain in this project for the scenarios when the contaminant is either dirt, dust, or water droplets that block vehicle sensor surfaces.

9. Participating parties and contact persons

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Research leader and Academic co-supervisor:	Johan Casselgren Luleå University of Technology johan.casselgren@ltu.se

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