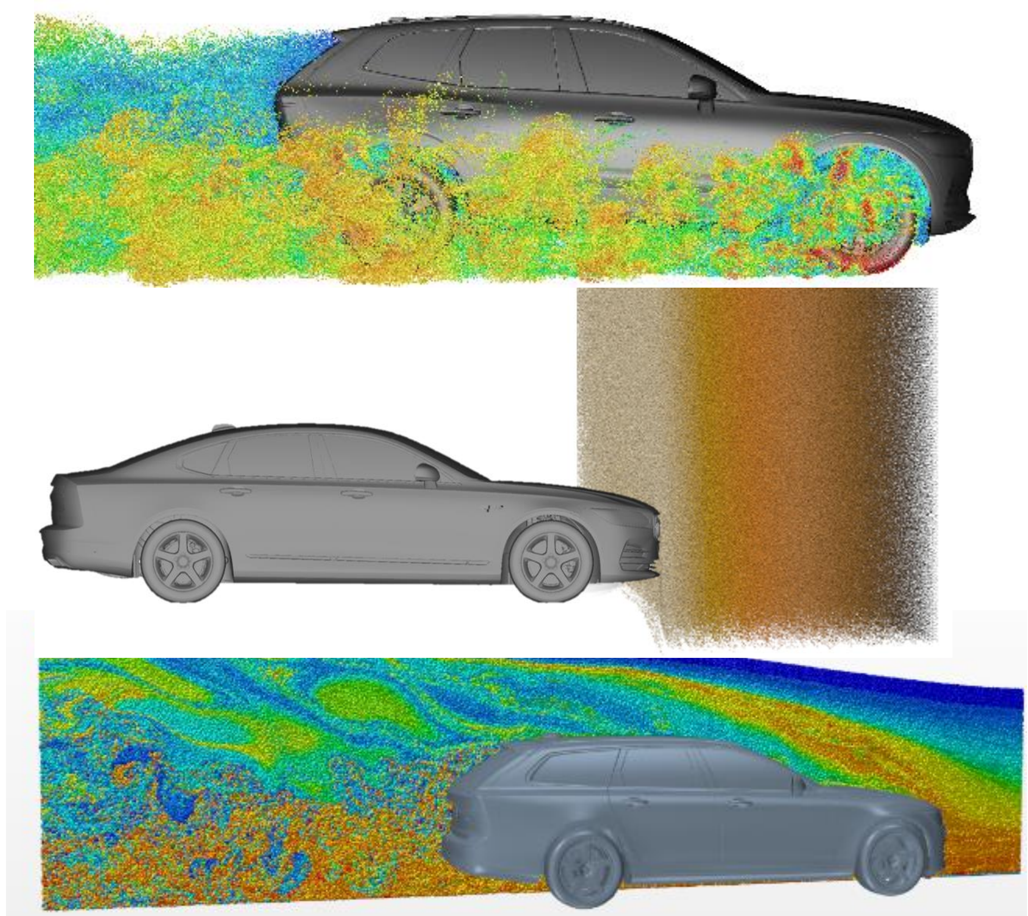
Modellering av radarförblindning i extrema snöförhållanden

Public report



Project within FFI -Trafiksäkerhet och automatiserade fordon
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Content

1. Summary

Vehicle safety has improved significantly the past decades thanks to the use of advanced sensors that complement the driver's vision. One limitation, however, is sensors availability does not reach 100 %, for example, during adverse weather conditions, sensors can be blinded by snow, rain or dirt. There is therefore a direct link between increasing traffic safety and ability to understand and predict sensors blindness. The physics which leads to agglomeration of snow on surfaces is complex and depends on the flow field around vehicles and chemical / physical interactions between snowflakes (particles) and the sensor surface. To deal with this issue, there is yet no established model. Therefore, this project focuses on providing innovative methods for estimating the radar blindness during extreme weather conditions. This will be done by creating new models of interaction between particles and surfaces and link them to vehicles flow calculations to improve the sensor's availability.

To do so, the project will use lateral innovation, in the sense that agglomeration and adhesion will be modelled by applying methodologies and models that are used today in the pharmaceutical industry. The academic partner is responsible for building a generic experiment for better understanding the physics and build/calibrate new models. Volvo Cars as industrial partner will apply models in car simulations and validate models through full scale tests in a climate wind tunnel. The resulting simulation method should open paths for more systematic studies of sensor availability, even in weather conditions that cannot be simulated in wind tunnels. The consequence is that it should be possible to make better sensor systems and get a better understanding of the limitations.

The value for industry partners will be a new method for addressing contamination of vital sensors with application to autonomous driving and active safety. In particular, it will open possibilities for optimizing the location of the sensors, finding robust layout and securing the attribute operation, even during extreme weather conditions. It will also open avenues for virtual design, decreasing the number of physical tests and simulate weather conditions that are not accessible in the wind tunnel.

2. Sammanfattning på svenska

Fordonsäkerheten har förbättrats betydligt de senaste decennierna tack vare användningen av avancerade sensorer som kompletterar förarens seende. En begränsning är dock att sensorns tillgänglighet inte når 100%, till exempel under ogynsamma väderförhållanden kan sensorer förblindas av snö, regn eller smuts. Det finns därför en direkt koppling mellan trafiksäkerhet och förmåga att förstå och förutsäga sensorns nedsatta funktion. Fysiken som leder till agglomerering och vidhäftning/adhesion av snö på ytor är komplex och beror på luftflöde runt fordon och kemiska/fysisk växelverkan mellan snöflingor (partiklar) och sensorns yta. För att hantera dessa frågor finns det ännu ingen etablerad modell. Därför

fokuserar projektet på att tillhandahålla innovativa metoder för att uppskatta radarblindhet under ogynsamma väderförhållanden. Detta kommer att ske genom att skapa nya modeller av interaktion mellan partiklar och ytor och länka dem till fordons beräkningar för att förbättra sensorns tillgänglighet.

För att genomföra projektet används s.k. lateral innovation, dvs kunskap och modeller utvecklade för en annan tillämpning (framställning av läkemedel) kommer att användas. Den akademiska partnern ansvarar för att bygga generiska experiment för att bättre förstå fysiken och utveckla/kalibrera nya modeller. Volvo Cars som industripartner implementerar modeller i bilsimuleringar och validerar modeller genom fullskaletest i klimatvindstunnel. Den resulterande simuleringsmetoden bör öppna vägar för mer systematiska studier av sensortillgänglighet, även i väderförhållanden som inte kan simuleras i vindtunnel. Konsekvensen är att det ska vara möjligt att göra bättre sensorsystem och få en bättre förståelse av begränsningarna.

Värdet för branschpartnern kommer att vara en ny metod för att hantera kontaminering av vitala sensorer med tillämpning på autonom körning och aktiv säkerhet. I synnerhet kommer det att öppna möjligheter för att optimera sensorernas placering, hitta en robust layout och säkerställa funktionalitet, även under extrema väderförhållanden. Det kommer också att öppna vägar för virtuell design, minska antalet fysiska test och simulera väderförhållanden som inte är tillgängliga i vindtunneln.

Inom projektet var målet att utveckla en CAE-prediktionsmetod för att bestämma snöexponering och dess effekter på sensorsystem. Med denna CAE-verktygslåda bör den tidiga fasproduktutvecklingen för sensorsystem stödjas för att designa ett system med ökad tillgänglighet vid ogynnsamma väderförhållanden.
Arbetspaketen inom projektet var uppdelade, så att Volvo Cars utvecklade den fluid dynamiska modellen av det kompletta fordonet, medan Postdoc på Chalmers fokuserade på detaljerade fysikaliska egenskaper av snö och modellering av agglomerering och adhesion.
Vi har fått goda kunskaper om detaljerade snöpartikelegenskaper (Figur 4) och data för snörpartikelstorlek, form och dess vidhäftningsegenskaper (Figur 6) kunde samlas in. Tyvärr har det visat sig vara en komplex uppgift att bestämma tillförlitliga detaljerade snöegenskaper för ett större antal snötyper. Därför inriktades fokus mot torrt snödamm medan våt snö kommer att studeras i framtida forskningsprojekt. En DEM-metod utvecklades för att förutsäga en stick-or-bounce-prediktionsmodell (Figur 7). Detta har fungerat mycket bra för torr snö och preliminära modeller för våt snö är utvecklade men arbetet kunde inte slutföras på grund av brist på fysikaliska data.

Den kompletta fordons CFD-modellen, som utvecklades inom detta projekt, kan förutsäga olika körscenarier (Figur 13):

- körande ensam på vägen
- körande i nederbörd
- körande bakom ett annat fordon.

CFD-modellen kan tillämpas på en mängd olika nedsmutsningstyper; Idag fungerar den robust för torrt snödamm. Exponering/kontaminering av sensorer för snö och andra föroreningar kan förutsägas. Modellen kunde inte kopplas direkt till en radarantennmodell, som skulle kunna förutsäga föroreningarnas exakta påverkan på radarprestandan. En sådan studie kommer att ingå i ett nytt doktorandprojekt.

3. Background

Recent progresses in active safety have reduced the number of collision and injuries on road. For example, analysis of insurance data reveal that active system for rear-collision avoidance reduced by 28% rear-collisions (Isaksson-Hellman and Lindman, 2015). Active systems are seen as crucial tool for mitigating accident on road and are getting wide-spread and more complex. Such systems include a variety of complementary sensors enabling a 360 degree view at all instants. These consists of cameras, lidars, radars and ultra-sound sensors, to cite a few (see figure1). One major limitation to the benefits of active safety systems is the availability of the system in time. For instance, deposition of water, snow or dirt impairs the performance of optical systems such as lidars and cameras. Since active safety systems build the foundation for the safety concept in modern vehicles it is required that, they are available at a wide range of weather conditions. It is even most relevant that they are fully functional at harsh and potentially dangerous environmental conditions, and therefore maintain sufficient optical access for all sensors at all time. Especially winter and snow conditions are crucial, since sensors such as radars or cameras are blocked nearly instantly by packed snow, while at the same the road conditions are more dangerous than in dry conditions. In the US alone, each year, 24 percent of weather-related vehicle crashes occur on snowy, slushy or icy pavement and every year, nearly 900 people are killed and nearly 76,000 people are injured in vehicle crashes during snowfall or sleet. (US department of transportation, 2017).

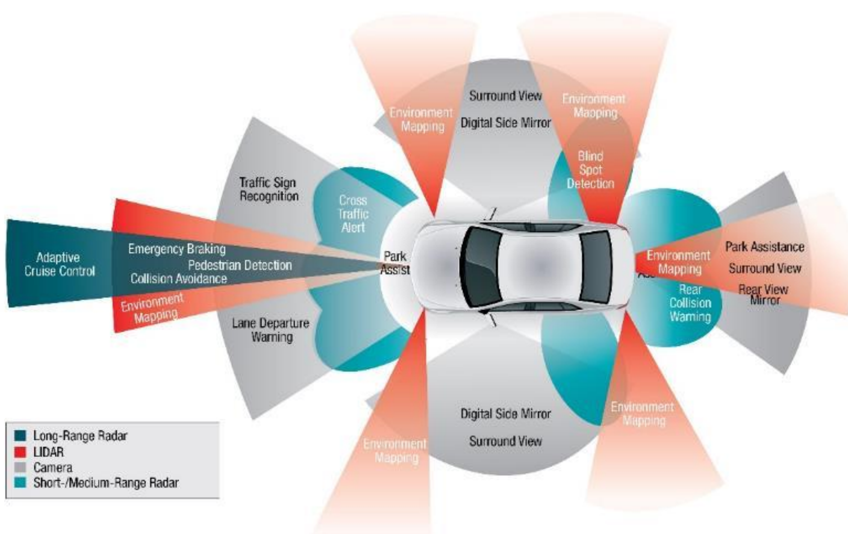

Figure 1: Sensor system for active safety and autonomous drive systems

To make autonomous driving systems a viable solution for private as well as for fleet customer, it is crucial to offer a robust system with a wide available concerning weather and soiling conditions. Private customer will only be satisfied with an AD system, which is robust and signals a high level of confidence. For fleet customers (taxi, car-sharing etc.) the number of groundings due to weather conditions will play a vital role for the availability and competitiveness.

Two complementary tracks are pursued, namely soiling avoidance and multi-purpose washing systems. Both tracks are, however, posing technical challenges. Soiling avoidance by selection of location, shape and surface properties of sensor requires deep understanding on contaminant particle trajectories and adhesion properties. Multi-purpose washing systems or electric heating systems, can only be applied to a limited number of sensors and always face a liquid or energy consumption problematic.

Since sensors are located at a large variety of locations around the vehicle, the optimisation for sensor contamination needs to be done at an early product development stage. For these reasons, we see the strong need for a virtual method, which describes and couples the effects of snow/water contamination and sensor performance. The aim is to secure the full functionality of all active safety components at all car speeds and offer a robust AD sensor system.

Virtual snow packing models will together with additional contamination CFD models build a toolbox, which can help guiding the design of automatized vehicles. Input from the model would be needed to influence the shape of the sensor surfaces, choice of sensor location and use of cleaning system in order to support efficient cleaning jointly with the prevention of contamination.

4. Purpose, research questions and method

The short-range damping effect has recently become of interest to the automotive industry, and some pioneer work is beginning to emerge. As an example, Hassen (2006) focused on radar mitigation due to water film. As far as the authors are aware, no work has been published about the accumulation of snow on the radar and subsequent signal attenuation. One reason is the difficulty of reproducing adverse weather conditions in wind tunnels for direct test of the onboard sensors.

It is also explained by the complexity of the involved physics. Wet snow consists of a crystal and liquid water that can agglomerate or stuck on the surface of the radar shell. It is a complex multi-physics problem (including phase change, surface forces, agglomeration, elastic reflections ...), and calls for further research to get a complete and easy-to-use model. So far, the problem of particles has not attracted much attention in the automotive sector, but is an established field in the pharmaceutical industry and food technology.

However, experimental techniques are limited to relatively simple systems and advanced numerical simulations are needed to move on in analysis. An appropriate method is therefore to combine experimental work with mathematical modeling. A recent review of Reeks (2014) goes through methods to model particle flows - all based on momentum balances for single particle and aggregate. Figure 2 exemplifies the use of DEM (Discrete Element Modeling, tracking of individual particles) to study the interaction between a small particles aggregate with one big particle. Such a study contributes with basic understanding that helps to develop and apply processes for design, operation and optimization of processing equipment.

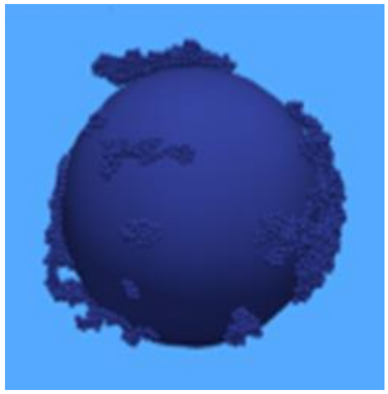

Figure 2: Small particles, which imping and agglomerate on a large carrier particle, (Nguyen et al., 2014)

For snow, the particles would consist of crystals or agglomerate of crystals. The moisture content in snow is an important parameter for the aggregation of the aggregates (Figure 3) and potential adhesion on solid surfaces. Therefore, the history of the snow plays (sequences of reheat / cooling) plays an important role in determining the size of the unit as well moisture content. It is expected that the method described in the previous paragraph can be utilized to address the current issue of interaction between snow and vehicle surfaces. There is therefore a great need to learn from the pharmaceutical industry and food technology, by adapting existing models to use to predict sensor performance in difficult weather conditions.

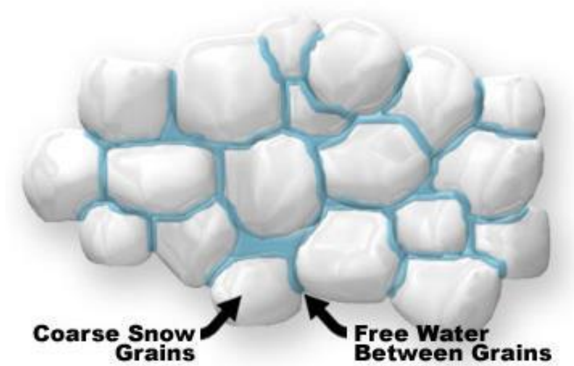

Figure 3: Wet snow agglomerate with water bound between solid particles
(*http://www.its.caltech.edu/~atomic/snowcrystals/photos/w031224c103.jpg)

5. Objective

Objectives

The purpose of the project is to increase the performance of radar sensors. To do this, we will build a virtual model to predict exposure to adverse weather conditions and predict sensor response and performance. It will result in a unique innovative modelling capability to study and minimize the effects of snow on active safety sensors. The research will focus on developing, implementing and testing new models to handle interactions between particles (snow) and surfaces (vehicle exterior and radar).
Specific goals with direct relevance to VINNOVA's goals:

1. Increase safety by improving the availability of the radar under adverse weather conditions aimed at reducing the number and severity of accidents.
2. Increase the use of calculation methods for the construction of the car's safety system with reduced lead times and lower costs.
3. Perform virtual testing in a variety of weather conditions - even those not reached during physical testing.
4. Provide simulation tools that allow optimum sensor / sensor placement for increased security.

Expected results

Developing new innovative physical models and numerical calculation methods, as well as tools to predict the reduction of radar performance in difficult weather conditions. This research project will be carried out mainly by connecting models for particle transport (based on Computational Fluid Dynamics - CFD) and new snow impingement models on surfaces. CFD codes used today at VCC will be supplemented with results from work at Chalmers within this project.
The result list consists of:

1. New knowledge database on detailed snow properties and behaviour in different climatic conditions.
2. New understanding of the physics that drives snow adhesion on surfaces.
3. New models that can predict snow formation on surfaces and reduced radar performance.
4. Implementation of these models in the VCC's complete vehicle CFD codes. To create a CFD model capable of predicting different snow driving scenarios.
5. Development and testing of a simulation method to predict vehicle radar performance in extreme weather conditions.

During the project the objectives and expected results were adjusted in alignment with the newly gain experiences. A larger focus was set towards determination of physical properties of snow particles and on the implementation into the complete vehicle CFD method.

It was crucial to determine snow particle properties and adhesion behaviour in detail in order to enable a complete vehicle CFD model. Since a large variation of properties with a high sensitivity to environmental conditions were discovered, the project content was lowered and the focus was put on detailed investigation of one specific type of snow, dry snow dust.
Intensified focus was set on developing a complete vehicle CFD model for snow dust contamination. It was judged as being crucial to have a robust model to predict the exposure to snow dust and other contaminants for a complete vehicle. The ambitious objective to predict sensor signal disturbances caused by contaminations had to be postponed. It was not possible in time and extend of the present project to develop a complex coupled model between the electromagnetic antenna model and the Multiphysics flow model. This should be content of a future project.

Application of results

The value of the project lies in a new calculation methodology and will be reflected in competence building for particle modelling in the automotive industry and the development of new models to be published in international journals. The calculation methodology shall be used for the development and evaluation of active safety systems for VCC's future car project. The new competencies in particulate matter and surface modelling will be used to initiate new activities to simulate contaminations in general and ultimately work towards 100% sensor availability.

6. Results and deliverables

Physical snow properties

It is known to us that the snow build-up on the vehicle exterior is very dependent on temperature and weather conditions. Snow in warmer conditions tends to stick on first direct impact, while cold and dry snow dust only build up in regions of low impact energy and low aerodynamic shear stresses. Finally it comes down to differences in the particle and adhesion properties of snow, which makes the differences between sticking to a surface or rebound from it.
As one part of the project, it was the idea to analyse the properties of infield snow samples, ranging from snowflakes from the air to snow from tire tracks on the road, to study the changes in shapes, sizes, and adhesion properties of the snow at one location. The tests were performed in northern Sweden in January 2016. The temperature and relative humidity of the air under the entire measurement period were logged. The measurements were made on the ground by the side of the road from which the snow was collected. All samples were collected using a dense feathered brush. The brush was used to gather samples into a container, to spread each sample on an examination plate for the microscope, and to pick aggregates to place on the load cell test plate for the adhesion tests. The samples

are from: snowflakes, untouched snow from the road, and snow from wheel tracks, suspended snow dust, and snow from a car at different locations, covering the entire range of snow types from the air to different locations on the car (Figure 4). The samples were analysed using the following tools: a microscope to take photos for shape and appearance and obtain particle size distributions; and an in-house adhesion cell to measure adhesion to the car material.

Figure 4. Snow particles a) untouched snow fresh falling b) from vehicle snow cloud

The experimental equipment for the adhesion and internal strength tests is shown as a sketch and photography in Figure 5. The equipment had a sensitive load cell to measure the adhesive forces between the snow and the test material. The load cell was an S-beam load cell provided by FUTEK with a capacity of 10g. The rated output was 0.5 mV/V, and the sampling frequency was 20Hz, which gave an estimated resolution of the force of approximately 0.4 dyne. The sampling frequency was chosen based on a trial in which the highest sampling rate was obtained with an accuracy that allowed for the resolution of force peaks. The cell was calibrated at 0C and had a temperature shift span of 0.02 % of load/F. The tests measured the adhesion forces between the material and the snow that would be relevant for snow smoke contamination from the road.

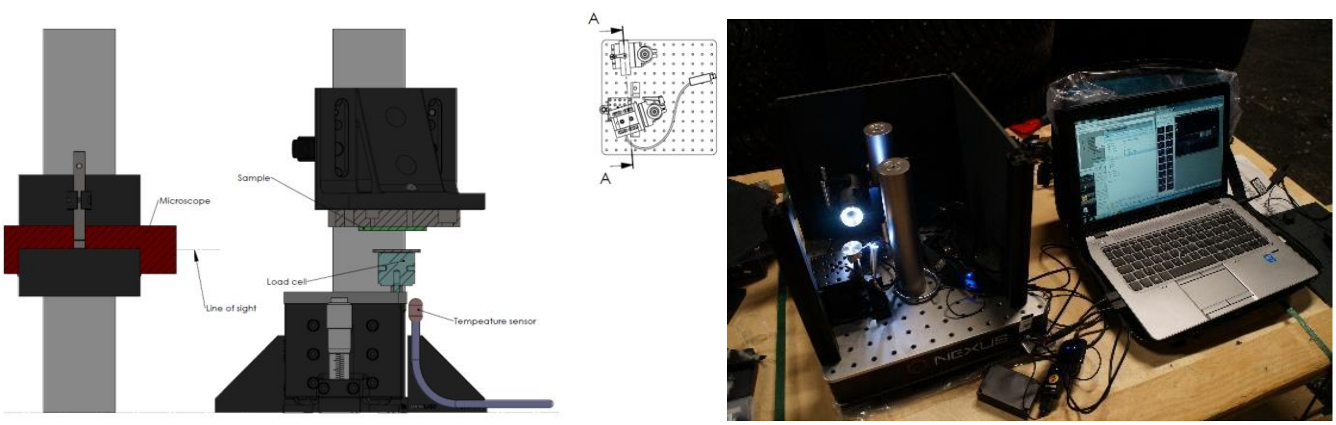

Figure 5. Test cell for snow adhesion measurements.

Snow particle from different locations were investigated. As an example only the particle size distribution (PSD) from suspended snow dust in a vehicle wake is shown here. The suspended dust PSD (Figure 6) shows a peak around 0.05mm diameter. It can be seen that particles as large as 1.2mm were also collected on the plate. The shape of the distribution is similar to a log normal distribution. Figure 4 shows a representative microscope image of the fresh fallen snow as well as suspended snow dust. The dust has been brushed together and it can be seen that the particles easily form clusters, which indicates that internal cohesion forces are present. Comparisons of snow collected at different places show that the snow on the road contains a broad range of particle sizes. The suspended dust mainly consists of smaller sizes and they contaminate the car in the following order: smaller dust particles end up higher up and on the back of the car while larger (1mm) particles can go inside the rims. This is in agreement with a Stokes number analysis, which defines the particle Stokes number as the particle response time scale over the relevant time scale of the flow. Independent of the choice of flow time scale, a smaller particle of the same material has a lower Stokes number and therefore follows the flow around the car better, can fly higher and, to a larger extent, enter the wake behind the car as well. Inside the rims, the air flow seems to hinder the entry of small Stokes number particles, while larger particles that are thrown up by the tire can, with their larger inertia and therefore higher Stokes number, enter the rim cavity.

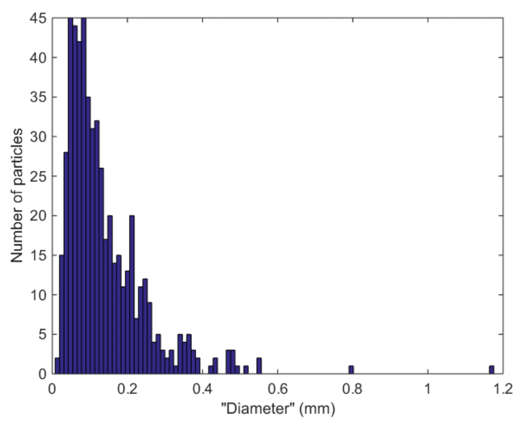

Figure 6. The PSD of collected suspended snow dust.

The measured adhesion force was in the range of 2 to 12 dyn. The force is comparable to literature values of ice adhesion for dry and cold conditions. The measurements show very little spread between the different snow types or collection spots. It is clear that the force measurements from the snow collected from the tail light of the car, shows a larger spread than the other measurements. This may indicate that these particles are stickier. The suspended dust shows somewhat higher adhesion forces than the road and rim snow types.

In addition to tests in winter snow dust conditions, tests were also conducted in wet road spray conditions to study the spray cloud and dirt gradient on the vehicle surface. Since the aerodynamics of fine particle is comparable between snow dust and fine sand dust, measurements of the dust cloud were also conducted on a test track in Arizona desert climate. Measurement in Arizona were conducted with an IR device to determine volume displacement by solid particles, from these data a time averaged mass flow distribution was determined.

DEM model

As part of the CAE model development it is required to determine the particle adhesion behaviour for all possible impact velocities and angles. Therefore it was decided to determine a regime map, which describes in which conditions a snow particle will stick or rebound from a surface. A discrete element model (DEM) based on the software LIGGGHTS was chosen to develop a virtual experiment setup (figure 7).

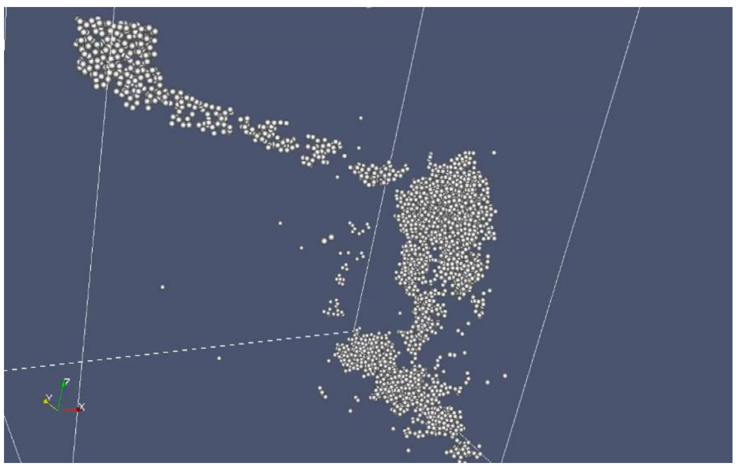

Figure 7. DEM particle impingement model to evaluate adhesion conditions

The experimental determined particle parameter for adhesion force are used as input together with literature values for coefficient of restitution and the elastic modulus into DEM model. The virtual experimental design is set up to simulate the impingement of a snow particle with a large range of normal and tangential velocities as well as different particle diameters. Within a next step in these calculations, it could be determined if a particle stuck to the surface or if it rebounded. The results made it possible to create a regime map, which describes if a snow particle sticks to a surface dependent on tangential impact velocity, normal velocity and particle diameter. This regime map is required for the CFD model to decide if a simulated particle should stick or rebound on the vehicle surface.

The virtual experimental design is capable to create impingement regime maps for all kinds of particle properties. But due to the limitations within the experimental campaign, only calculations for cold and dry snow were conducted. The particle properties and DEM model capabilities were later extended to be able to handle wetness in between snow particles.

Complete vehicle contamination CFD model

The complete vehicle CFD model is based on an Aerodynamic model used to predict aerodynamic drag and lift forces on the complete vehicle. Into this pure aerodynamic model, particle will be injected, which represent the presence of snow. The model approach is independent on the used software, but it was developed in Ansys Fluent and Siemens StarCCM+ in parallel. The air phase is simulated as continuous phase in an Eulerian-approach, while the particles are simulated as discrete phase in a Lagrange-approach. A crucial part in the description of self-contamination by snow is a sufficient representation of the particle trajectories through the continuous domain. In a Lagrangian particle model, the particle trajectory is calculated by its force balance, which incorporates the gravitational force, aerodynamic drag and inertial forces. The drag component is the part, which couples the discrete particle to the continuous aerodynamic phase. The relation between the inertial forces and drag forces for a particle describes its trajectory, and how well the particle can follow the continuous air phase. For a relatively large and heavy particle, the inertial forces would be much larger than the aerodynamic drag and consequently, the particle would not follow the aerodynamic streamlines. That is for example valid for stones, large water drops or lumps of snow.

For relatively small and light particles, the drag force dominates the force balance. That means that these particles can follow the aerodynamic streamlines and even unsteady flow structures. Particles would be carried by the airflow and in regions of large unsteady flow structures, the particle dispersion would be governed by these flow structures.

In a first approach a steady state CFD model was developed using a k-epsilon turbulence model for the continuous phase. After convergence for the aerodynamic model was reached, the particle model was activated and steady state particle tracking delivers a time averaged particle concentration. Particle tracking in a steady state CFD framework will deliver a steady state particle concentration. Injected particles would only be able to follow these time averaged streamlines. In order to model the particle dispersion due to turbulence in the flow field a particle dispersion model was applied. The random walk dispersion model adds a random disturbance to the particle trajectory at each iteration step.

A shortcoming of the steady state method is that large scale unsteady flow structures are not captured. The random walk method can model dispersion due to small turbulent structures, but is not sufficient to model large scale unsteady structures. As we have established that the snow-particles are small and light, they are able to follow aerodynamic flow structures. In regions were unsteady flow structures are dominating, such as behind the front wheels and at the rear wake of the vehicle, the particle dispersion is governed by large scale structures. With these vortices particles can be carried far away from the time averaged streamlines. As a consequence, it is required to resolve unsteady flow structures in order to predict the accurate particle distribution and impingement on the vehicle.

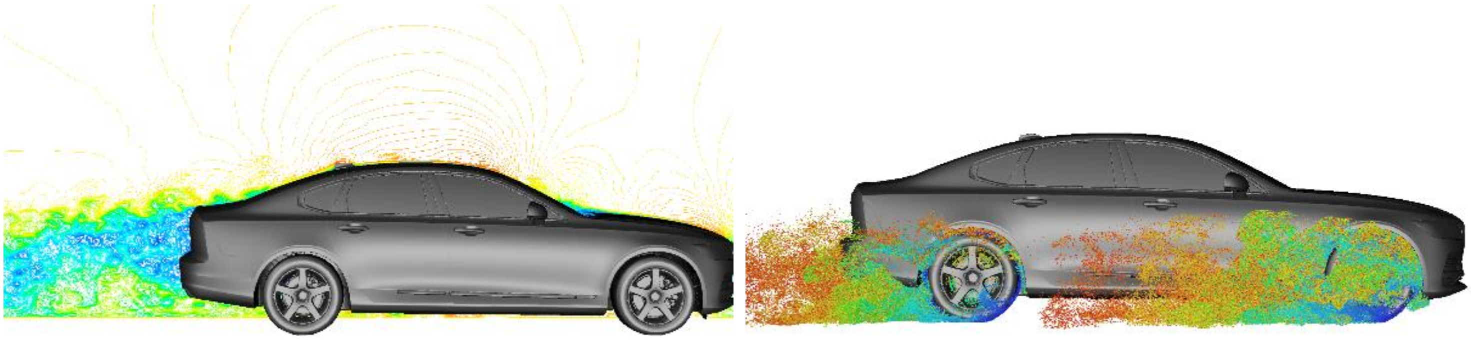

Figure 8. a) Unsteady aerodynamic simulation and b) with addition of particle simulation

The developed unsteady CFD model (Figure 8), is based on the complete vehicle aerodynamic model with a DDES turbulence model. The volume mesh for that model is build up by approximately 200 million cells including prism layers on all surfaces. In order to resolve unsteady structures, sufficiently small time steps of 0.0002s are required. In each of these time steps 10.000 particles are injected, and new positions for all particles in the domain are calculated. When distancing further than 4.5m behind the car, particles are deleted from the domain. Simulation procedure begins with a pure aerodynamic simulation until the continuous phase converges, when particle injection is started, the number of particles will continuously increase until the number of particles leaving the domain is equal the number which is injected. In that state of balanced in and out mass flow, approximately 10million particles are tracked inside the domain. Simulations were run and data collected for 4s simulated time, which puts a large demand on high performance recourses, on 1000 computational cores the simulation requires approximately 72h.
It is crucial to capture a correct particle distribution in the cloud around the vehicle, therefore simulation data were compared to measurement from Arizona desert dust track. Figure 9 shows cut planes of time averaged particle concentration around an S90 from CFD simulations, the red regions describe larger particle concentration.

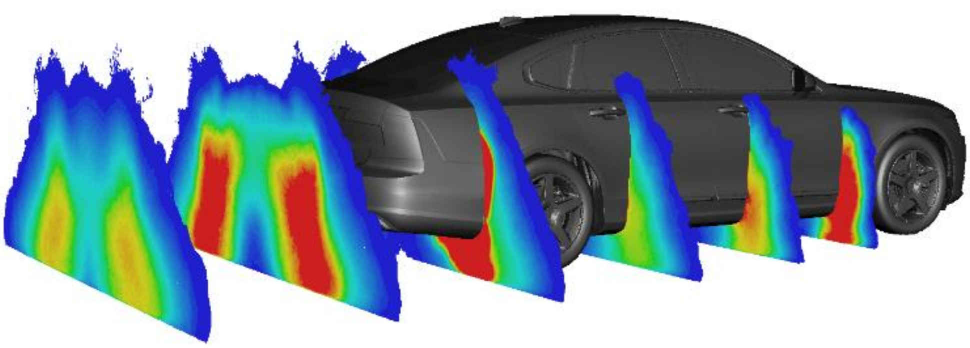

Figure 9. Time averaged particle concentration representing the snow dust cloud

The particle boundary condition describes the behavior of the particle when colliding with a surface. By default, in the standard software, that is either always set to reflect or always absorb. For the complex case of snow a new impingement boundary condition needed to be programmed. Since the detailed simulation of each collision of over 10 million particles is computationally not feasible, the approach using a regime map was developed.
The DEM model delivered a regime map which describes under which conditions (normal velocity, tangential velocity and particle diameter) a particle would stick to the surface. The boundary condition in the CFD model was programmed to check if these conditions are fulfilled in case of an impact and consequently set the particle to “stick” or “rebound”. If a snow-particle sticks to the surface in the simulation, its mass is added to the surface cell and tracking is deleted; if a particle rebounds, it does not leave any mass to the surface and continuous to be tracked in the aerodynamic domain.

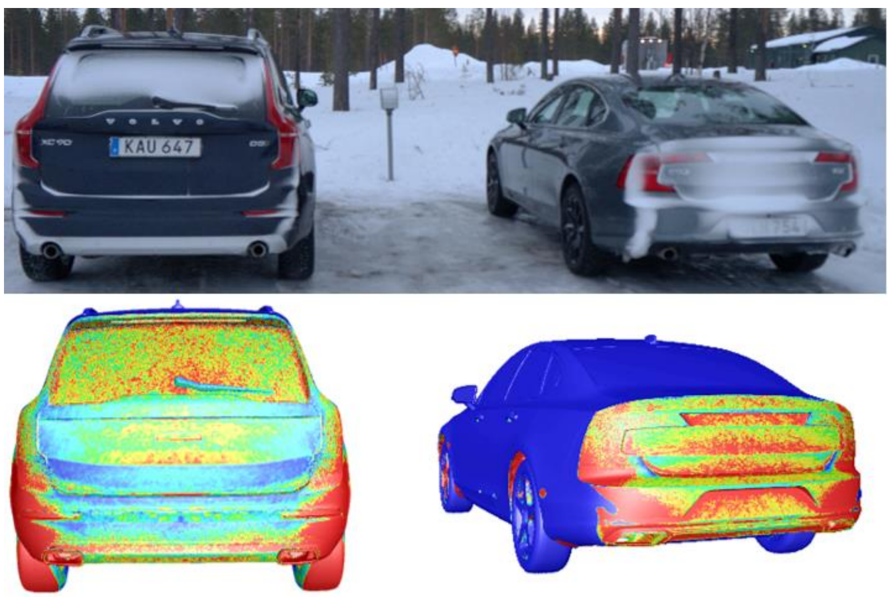

Figure 11. Field tests for snow packing and simulation results with CFD model

In every calculated time step new particles are colliding with the surface and may add mass to a surface cell. In this way it was possible to simulate the continuous collection of snow mass onto the surface of the vehicle. After 4s of simulated time a representative continuous gradient of particle concentration could be achieved. The impingement boundary condition is programmed in such way that a regime map describing any type of particle could be used in the boundary condition. Thus it should be possible to determine new impingement behaviours for i.e. wet snow and directly implement that into the CFD model.

Results were compared to complete vehicle field tests on the winter test track in northern Sweden. In the cold and dry climate conditions in northern Sweden, large amounts of snow dust is lifted by the vehicle and builds-up on the vehicle exterior, underbody and sensor surfaces. But due to the dry and non-adhesive properties of the snow dust, it does only stick and build-up in regions where snow impinges with low normal and tangential velocities. Figure 11 shows a typical snow build-up after short driven distances on snow covered roads at temperature under -15C. Figure 11 also shows the simulation results for the same conditions, where the colours describe the collected mass of snow-particles. It can be seen that the boundary condition has prevented any snow mass to be collected on the side of the vehicle, where large tangential velocities dominate the impact. This agrees very well with field tests. The gradients of mass concentration in simulations (large mass concentration is described by red) also agrees rather well with results from field tests. But field tests are always compromised by weather variations, road conditions and complexities such as influence of exhaust gas heat.

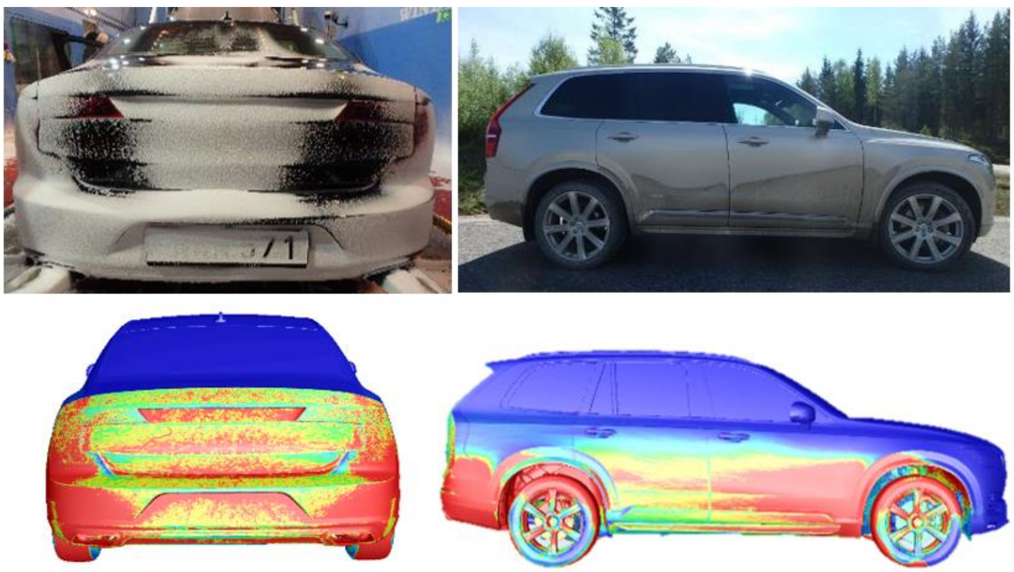

Figure 12. Wind tunnel tests for snow and gravel tests compared to results from CFD

Therefore validations for the simulations were also conducted in the Volvo full scale climatic wind tunnel. In the climatic wind tunnel it is possible to generate snow dust and test complete vehicle in wind speeds up to 200kph. To validate the simulation method, a generic simplified test object was constructed; this test object was shaped like a 1.5m x 1.5m x 0.5m large wedge. Simulations and tests were conducted and published in a master thesis. Wind tunnel test were also conducted on complete vehicle to eliminate external influences which are not accounted for in simulations. Figure 12 shows snow build-up in the climatic wind tunnel in comparison to simulation results.
Since the simulation framework should be possible to handle other types of impingement conditions, test were conducted on the Volvo gravel road test track and evaluated against simulations where particle mass is collected on every impact. Figure 12 shows these results and it shows clearly that the gradient for dirt exposure was predicted very well in the simulations.

Of course it is not the only relevant scenario for vehicle contamination and sensor dirt exposure if a car drives alone on snow covered road. But aerodynamically it was determined as the most complex scenario to capture unsteady flow structures around the wheels and in the wake. It was deemed that if succeeding in self-contamination, the CFD model could be extended towards other soiling scenarios easily. In the last part of the development of the CAE framework, the contamination toolbox was extended by the two additional driving scenarios; Driving in free fall precipitation and Driving behind another vehicle. Each scenario bases on exactly the same unsteady DDES simulations as earlier described, but have different particle injection schemes.

Driving in free fall precipitation injects particles as a constant randomized wall of snow uniform mass flow, which should be similar to driving into falling snow.

When driving behind another vehicle in real life, the air flow is not stationary and the snow cloud is not uniform. Since these are rather large differences to the free falling snow scenario, it was decided to add that complexity into the CAE toolbox. Due to computation recourses it is not feasible to conduct one simulation with two cars at the same time. For the "driving behind another vehicle" simulations, a first step simulation "self-contamination" is used to create the inlet conditions for the new simulations. The time averaged air velocities and the time averaged particle concentrations are sampled behind the first vehicle and used as inlet conditions for the simulations of a following vehicle. The sampled inlet can be reused multiple times for different vehicles. The different contamination scenarios are shown in Figure 13 and all of them can be freely combined to capture i.e. "driving on snow covered road behind another vehicle".

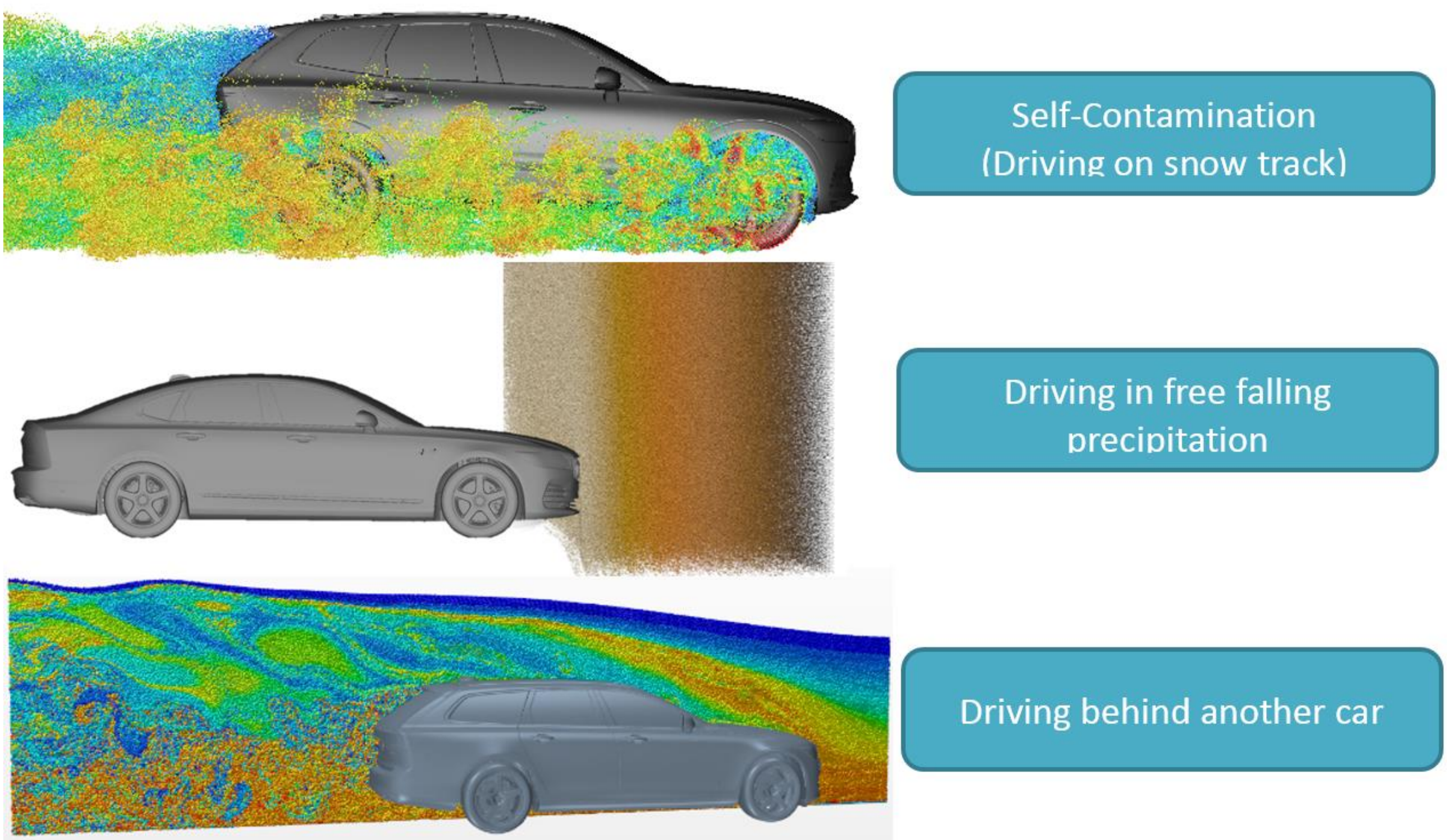

Figure 13. Road contamination prediction methods within complete vehicle CFD model

Throughout the project, the targets and plans were adjusted. On one side to stay feasible and match discovered problems, on the other side to utilize newly discovered potential.
As mentioned earlier, while the project target was to predict snow build-up on different snow types, the content needed to be adjusted. While experimental data were only collected for dry cold snow, the CAE framework is open for additional snow types for future works. Also it was not possible within this project to directly couple CFD soiling data to an antenna calculation model. Since it is still rated highly relevant, this will be among others content of a new PhD project starting 2018.
On the other hand, the project content was extended towards a simulation approach for dirt and for gravel. It was identified that the modelling approach can be easily adjusted to describe the trajectories and impingement of particles other than snow. With some adjustments it was possible to develop a CAE model for stone impacts and predict exposed regions and predict general dirt patterns.

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	Experiences of that study helped us to understand and characterize different contamination exposures and their dominating physics. We gained experiences which have also helped us developing test methods.
Be passed on to other advanced technological development projects	X	We are right now starting up an industrial PhD project which is based on the findings and experiences of the present study.
Be passed on to product development projects	X	Product development for sensor systems for active safety as well as autonomous drive is already benefiting by the contamination prediction methods developed within that project.
Introduced on the market		
Used in investigations / regulatory / licensing / political decisions		

7.2 Publications

An infield study of road snow properties related to snow-car adhesion and snow smoke
P. Abrahamsson, M. Eng, A. Rasmuson
Journal title: Cold Regions Science and Technology 145 (2018) 32-39.

CFD modeling of snow adhesion on cars using DEM-based stick or bounce regime maps
P. Abrahamsson, M. Enmark, M. Eng, A. Rasmuson
- in manuscript

A dry snow accretion model for snow smoke made up of equilibrium rounded grains
P. Abrahamsson, A. Lind, J. Olsson, M. Eng, M. Khalilitehrani, A. Rasmuson
- in manuscript

DEM Modeling of Snow-Wall Adhesion - Development of a particle stick or bounce regime map for prediction of snow accumulation on cars
Anders Lind
Master thesis – Chalmers University of Technology (2017)

CFD Modeling of Snow Contamination on Cars - Implementation of a Snow Adhesion Regime Map by User Defined Functions
Markus Enmark
Master thesis – Chalmers University of Technology (2017)

8. Conclusions and future research

In a first phase, the characterization of snow different snow types and conditions was conducted. We gained lot of knowledge about snow properties. Not only fresh snow, but also compressed snow on road surfaces and airborne snow in the wake of a vehicle were investigated. Useful knowledge was gained concerning snow particle shape, particle size and their structure when agglomerating on a vehicle surface. In a second experimental campaign, the adhesion properties of snow particles were investigated. These experiments are required as input parameter before the development of a CAE model would be possible. A discrete element modelling (DEM) approach was used to develop a virtual experiment setup, in which the collected experimental data are used and snow impacts of a large variety of speeds and angles are virtually performed. The results of the stick-or-bounce behaviour from that virtual experiments are leading to a prediction under which conditions snow will stick and build up on a surface or will rebound due to its impact forces.
The complete vehicle fluid dynamic model will incorporate the gained data of stick-or-bounce and be able to predict at which regions in detail snow will build up on a vehicle driving in certain conditions. Therefore a complete vehicle fluid dynamic model (CFD), which models the snow cloud around a driving vehicle, was developed. The CFD model is predicting the snow particle trajectory for three different driving scenarios (Figure 13):

- Self-contamination; vehicle driving alone on snowy road
- Precipitation; vehicle driving in falling snow
- Foreign-contamination, vehicle driving in snow dust cloud of another car

The particle impact model from the DEM approach is used to predict in which regions snow will stick and build up on the vehicle surface. This model can help to design sensor location and shape in order to optimize for minimal exposure. If exposure to snow and other contaminants is inevitable, cleaning systems can be developed already in early product development phases.

A future PhD project between Volvo Cars, Chalmers and Luleå will start in early 2018 and continue the work as well as investigate additional targets. The industrial PhD project will aim to solve complexities of snow packing and agglomeration in order to predict sensor availability and support the design of robust systems. Therefore, three-dimensional snow agglomeration and build-up should be described and a workflow needs to be developed to couple to antenna performance simulations. Additional research needs for future projects are within the CAE modelling of different surface properties (i.e. hydrophobicity) and their effect on snow adhesion as well as water droplet formation.
There will be more need in the future for CAE prediction methods and tools for design optimization on general vehicle contamination as well as sensor availability.

9. Participating parties and contact persons

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