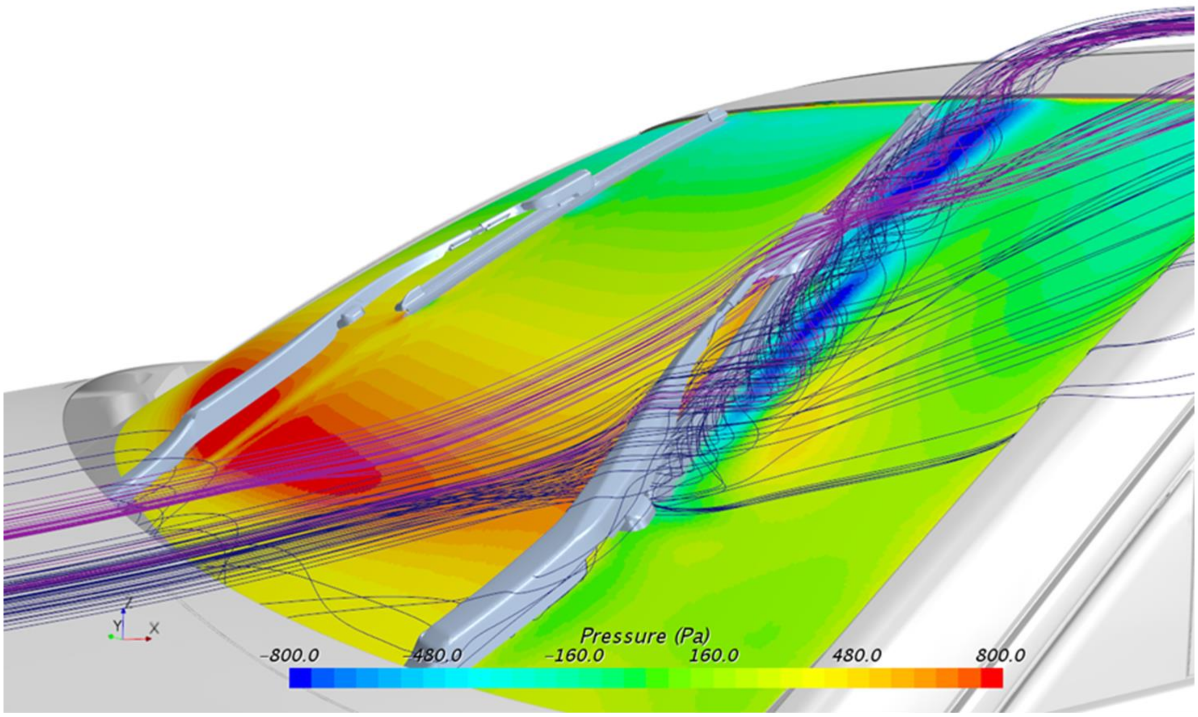
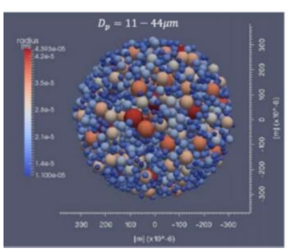
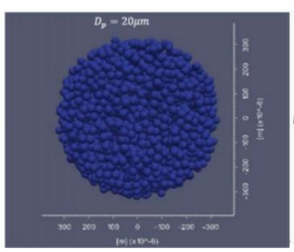
# Sensor Cleaning

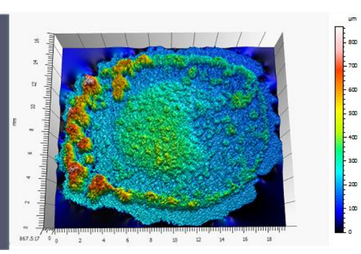
## – Virtual tool for cleaning performance to maintain availability of AD sensor system

**Public report**



Project within FFI -Trafiksäkerhet och automatiserade fordon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# Content



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# 1. Summary

Active systems in cars 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, LiDAR, radars and ultra-sound sensors, to cite a few. One major limitation to the benefits of active safety systems is the availability of the system in time. For instance, deposition of rain, snow or dirt impairs the performance of optical systems such as cameras, sensor and LiDAR. Cleaning systems are therefore vital for securing the benefits of active safety systems, especially in respect to autonomous vehicles. Cleaning systems are for now limited to maintain visibility for the driver which is subjectively assessed by the driver himself. With the increased importance of active safety and especially with the usage of autonomous drive systems it is crucial to maintain sufficient optical access for all sensors at all time. It is known that cameras, but also sensors like radar and LiDAR need a certain optical access and that their signal will be blocked due to i.e. rain, snow, heavy dirt or a water film. At harsh and potentially dangerous road conditions, such as snow, heavy rain or frost (salted roads), but also for everyday driving on rain, dirt or gravel active cleaning of sensors is needed to maintain the availability of the active safety and autonomous drive systems.

With increasing need of sensor cleaning, the usage of cleaning liquid is expected to increase. Increased usage of cleaning liquid will emit more harmful substances into the environment, but also add significant to the total weight of the car, when the liquid storage has to be increased.

Sensor can be located at different locations on the vehicle, one sensor cluster is behind the wind screen in the rear view mirror, and other sensors are located at bumper height, in the car centre or edges. The different locations are differently demanding concerning contamination and consequently their cleaning. On the wind screen, the complex interaction between wiper motion, water film and surface dirt is a multiphysics phenomenon. At locations which are exposed to the free air stream, the cleaning spray is heavily influenced by the air flow as a consequence of the driven speed.

Therefore in this project a CFD computational fluid dynamic model of wiper cleaning system and a mathematical model for dirt dissolution is develop. This complex CFD model include; moving wipers on the car windscreen, wiper-fluid interaction, fine droplet sprays, detailed car and wipers geometry and the aerodynamic forces.

The deposition and adhesion of solid particles on surfaces is usually an unfavourable phenomenon and is termed as fouling, incrustation or dusting, all of which happen on a daily basis in nature, industries and humans' life. The deposited particles in the latter phenomena are commonly referred to as “dirt”. These particles find a stable state because of the dissipation of free energy leading to formation of static patterns.

Convection and evaporation, among others, are two energy dissipating mechanisms which build most of the patterns formed in nature. Such mechanisms are integrated within the process of convective drying of wet particulate systems. Through the latter process, while drying densifies the solid particles in the suspension, convection pushes the fluid to move faster than the congealed particles in the direction of the shear. Subsequently, due to the mechanical instabilities originated by the process, convective drying of suspensions can lead to complex and heterogeneous morphologies. A common form of dirt consists of wet or dry dust with salt or other minerals which dries and adheres to surfaces. The result of such deposition, is a strongly adhered crust over the surface. This can cause minor and major issues including hindering visibility through glass surfaces or even impeding optical and sensory systems. Recently, these problems have gained importance in the automotive industry, since many of the safety and autonomous driving systems are based on optical and sensory systems. Specifically, when driving in wet roads, suspensions of dirt are spread over the exterior surfaces of the vehicles and dried through the surrounding convective air flow caused by the relative velocity of the car compared to the surrounding air. Formation of such dirt crusts can either prevent the detection of a real hazard or lead to an incorrect detection of an approaching object. Nowadays, the active safety systems in cars are quickly developing and have significantly reduced the number of collisions and injuries on the roads. However, the failure of these systems, for instance via such dirt deposition, can lead to hazards since modern day drivers are becoming accustomed to having such safety features in place to protect them and as a result are becoming less alert when driving.

A thorough literature study and detailed experimental investigation of artificial test dirt which consists of water, sodium-chloride and sand particles, has been conducted by the university partner to develop a dirt dissolution model which can be implemented into the CFD model of wipers cleaning system. The study investigate wet and dry particles and agglomerates impact behaviour at different moisture contents, impact energies, deposition and adhesion of the agglomerates. Through study and experimental measurement and numerical simulation the physical properties and parameter of the agglomerates has been determined.

Through this virtual CFD model it is now possible to analysis, optimize and study performance of wiper cleaning system, optimize washer liquid distribution on the car windscreen, washer liquid consumption, predict the cleaning performance of sensor and camera cleaning, early detection of problems and providing an option to test alternative designs and spray/wiping patterns not easily accessible in the lab.

# 2. Sammanfattning på svenska

Aktiva säkerhetssystem i bilar ses som ett viktigt verktyg för att minska olyckan på väg och blir mer och mer komplexa. Sådana system innefattar en mängd kompletterande sensorer som möjliggör en 360 graders vy vid alla tillfällen. Dessa består av kameror, LiDAR, radars och ultraljudsensorer. En viktig begränsning till fördelarna med aktiva säkerhetssystem är systemets tillgänglighet i tid. Till exempel påverkar avsättning av regn, snö eller smuts prestandan hos optiska system som kameror, sensorer och LiDAR. Rengöringssystem är därför avgörande för att säkerställa fördelarna med aktiva säkerhetssystem, särskilt när det gäller autonoma fordon.

Rengöringssystem är för tillfället begränsade för att bibehålla synligheten för föraren som är subjektivt bedömd av föraren själv. Med den ökade betydelsen av aktiv säkerhet och speciellt med användningen av autonoma drivsystem är det avgörande att bibehålla tillräcklig optisk åtkomst för alla sensorer hela tiden. Det är känt att kameror, men även sensorer som radar och LiDAR behöver viss optisk åtkomst och att deras signal kommer att blockeras på grund av regn, snö, smuts eller vattenfilm. Vid kraftiga och potentiellt farliga vägförhållanden, såsom snö, kraftigt regn eller frost (saltade vägar) men också för daglig körning i regn, smuts eller grus behövs aktiv rengöring av sensorer för att behålla tillgången på de aktiva säkerhets- och autonoma drivsystemen.

Med ökat behov av rengöring av sensorer förväntas användningen av rengöringsvätska öka. Ökad användning av rengöringsvätska kommer att avge mer skadliga ämnen i miljön, men också lägga till betydande vikt för bilens totala vikt när vätskeförbrukning måste ökas.

Sensorn kan placeras på olika ställen på fordonet, ett sensorkluster ligger bakom vindruan i backspegeln och andra sensorer är placerade i stötfångarens höjd, i bilens mitt eller kanter. De olika ställena är olika krävande föroreningar och därmed deras rengöring. På vindrutan är det komplexa samspelet mellan torkarrörelse, vattenfilm och yt-smuts ett multifysiksfenomen. Områden som utsätts för den fria luftströmmen påverkas rengöringssprayen kraftigt av luftflödet som en följd av den drivna bil hastigheten.

Därför utvecklas en CFD beräkningsmodell av torkarrengöringssystem och en matematisk modell för smutsupplösning. Denna komplexa CFD-modell inkluderar; rörliga torkarblad på bilens vindruta, torkarblad och vätske interaktion, droppspray, detaljerad bil och torkarblad geometri och de aerodynamiska krafterna.

Deponeringen och vidhäftningen av fasta partiklar på ytor är vanligen ett ogynnsamt fenomen och betecknas som grovbildning, inkrustning eller dammning, som alla sker dagligen i naturen, industrin och människans liv. De avsatta partiklarna i de senare fenomenen benämns vanligen "smuts". Dessa partiklar finner ett stabilt tillstånd på grund av spridningen av fri energi som leder till bildandet av statiska mönster. Konvektion och avdunstning är bland annat två energiutsläppande mekanismer som bygger de flesta av de mönster som bildas i naturen. Sådana mekanismer är integrerade i processen för konvektiv torkning av våta partikelformiga system.

Genom den senare processen pressar konvektionen, under torkning av de fasta partiklarna i suspensionen, vätskan att röra sig snabbare än de tätande partiklarna i skjuvans riktning. Därefter kan konvektivt torkning av suspensioner på grund av de mekaniska instabiliteter som härrör från processen leda till komplexa och heterogena morfologier. En vanlig form av smuts består av vått eller torrt damm med salt eller andra mineraler som torkar och vidhäftar ytor. Resultatet av sådan avsättning är en starkt vidhäftad skorpa över ytan. Detta kan orsaka små och stora problem, inklusive att hindra synlighet genom glasytor eller till och med hindra optiska och sensoriska system. Nyligen har dessa problem blivit viktiga inom bilindustrin, eftersom många av de säkerhets- och autonoma drivsystemen är baserade på optiska och sensoriska system. Specifikt vid körning på våta vägar sprids smutsutsläpp över fordonets yttre ytor och torkas genom det omgivande konvektiva luftflödet som orsakas av bilens relativa hastighet jämfört med omgivande luft. Bildandet av sådana smutsskorpor kan antingen förhindra detektering av en verklig fara eller leda till en felaktig detektering av ett närliggande föremål. Numera utvecklas de aktiva säkerhetssystemen i bilar snabbt och har avsevärt minskat antalet kollisioner och skador på vägarna. Felet i dessa system, t.ex. via sådan smutsavsättning, kan dock leda till faror, eftersom moderna förare är vana vid att ha sådana säkerhetsfunktioner på plats för att skydda dem och som ett resultat blir mindre varna vid körning.

En grundlig litteraturstudie och detaljerad försöksundersökning av artificiell test smuts som består av vatten, natriumklorid och sandpartiklar har genomförts av universitetspartnern för att utveckla en smutsupplösningsmodell som kan implementeras i CFD-modellen för rengöringssystem för torkarblad. Studien undersöker våta och torra partiklar och agglomerater som påverkar beteendet vid olika fuktinnehåll, slagkraft, deponering och vidhäftning av agglomeraten. Genom studier och experimentell mätning och numerisk simulering har de fysikaliska egenskaperna och parametrarna för partiklar och agglomeraten bestämts.

Genom denna virtuella CFD-modell är det nu möjligt att analysera, optimera och studera prestanda av torkarens reningssystem, optimera spolvätskedistributionen på bilens vindruta, spolvätskekonsumtion, förutsäga rengöringsprestandan av sensor och kamera rengöring, tidig upptäckt av problem och tillhandahålla ett alternativ att testa alternativa konstruktioner och sprej/torkningsmönster som inte är lättillgängliga i labb miljön.

En tredimensionell CFD-simuleringsmodell utvecklades i detta projekt. CFD torkar systemmodellen korrelerade väl med det fysiska testet av torkarens prestanda.

Den konstgjorda testsmutsen som används för att utvärdera rengöringsprestanda studerades i detta projekt för att hitta dess egenskaper för vidhäftning och avsättning. Genom akademisk forskning och experiment av smutspartiklarna och agglomeratet utvecklades en smutsavlägsnande modell. Smutsavlägsningsmodellen definieras som en formel som kan implementeras till CFD-torkar-systemmodellen. Smutsavlägsningsmodellen är ännu inte mogen för att ersätta rengöringsprestandan för fysisk torkarblad utvärdering men kan användas för rengöring av sensorer och kameror för att optimera rengöringssystemet för sensorer och kameror. Med CFD-torkarmodellen kan fordonets torkar system och sensor- och kamera rengöringssystem optimeras i tidiga stadier av produktutveckling.

# 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 camera. Cleaning systems are therefore vital for securing the benefits of active safety systems, especially in respect to autonomous vehicles. Two complementary tracks are pursued, namely water repellent paints (self-cleaning) and multi-purpose washing systems. Both tracks are, however, posing technical challenges. Water repellent surfaces use hydrophobic coating that are only usable on small surfaces. Multi-purpose washing systems, as used today, spray solutions of water/ethylene glycol eventually ending up on the road and further in the soils.

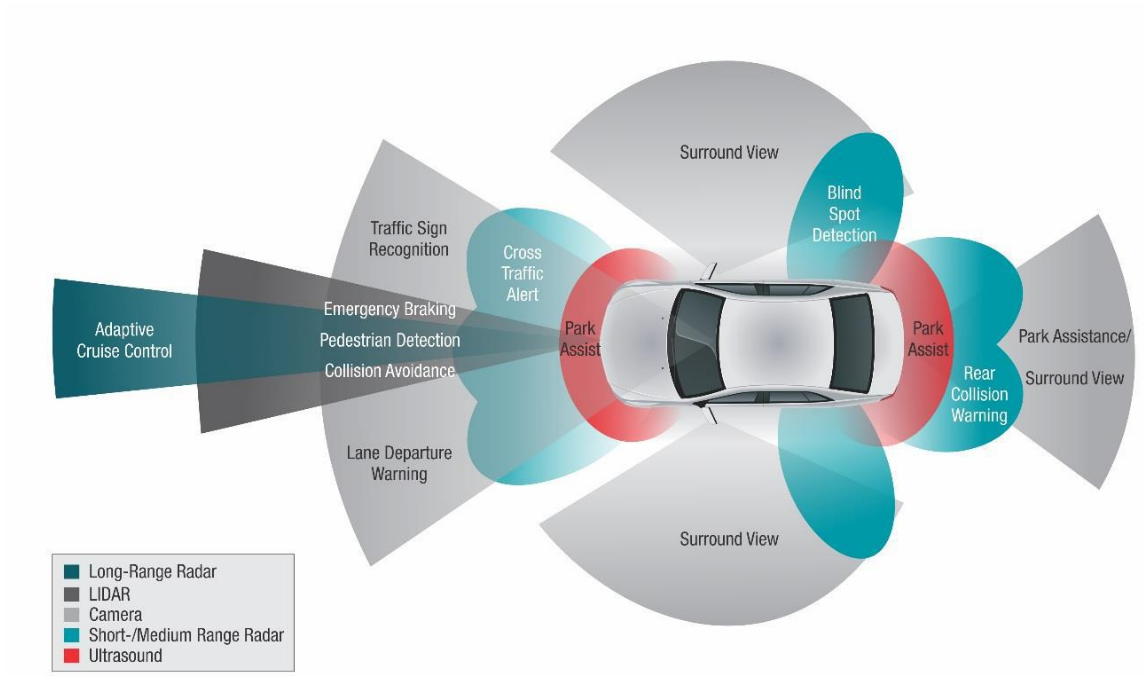


*Figure 1 Sensor system for active safety and autonomous drive systems*

Cleaning systems are for now limited to maintain visibility for the driver which is subjectively assessed by the driver himself. With the increased importance of active safety and especially with the usage of autonomous drive systems it is crucial to maintain sufficient optical access for all sensors at all time. It is known that cameras, but also sensors like radar and LiDAR need a certain optical access and that their signal will be blocked due to i.e. rain, snow, heavy dirt or a water film. At harsh and potentially dangerous road conditions, such as heavy rain, snow or frost (salted roads), but also for everyday driving on rain, dirt or gravel active cleaning of sensors is needed to maintain the availability of the active safety and autonomous drive system.

The virtual model for cleaning system and dirt adhesion and dissolution could be used for future self-assessment software system, in which sensors would predict cleaning need before a blockage accurse.
With increasing need of sensor cleaning, the usage of cleaning liquid is expected to increase. Increased usage of cleaning liquid will emit more harmful substances into the environment, but also add significant to the total weight of the car, when the liquid storage has to be increased.
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. The different locations are differently demanding concerning contamination and consequently their cleaning. On the wind screen, the complex interaction between wiper motion, water film and surface dirt is a multiphysics phenomenon. At locations which are exposed to the free air stream, the cleaning spray is heavily influenced by the air flow as a consequence of the driven speed.
For these reasons, we see the strong need for a virtual method which describes and couples the effects of wiper/water film interaction, fine droplet sprays and especially the dissolution of dirt particles from a surface. The aim is to secure the full functionality of all active safety components and autonomous driving techniques in all car speeds. Virtual cleaning models will together with already developed contamination 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 car speed dependent spray injection in order to support efficient cleaning jointly with the prevention of contamination.
A more efficient (speed dependent) application of cleaning liquid would also have less environmental pollution (ethylene glycol) and less total vehicle weight as a consequence.

# 4. Purpose, research questions and method

Historically, most widespread cleaning system are wind screen wiper and headlamp cleaning (HLC) systems using both cleaning liquid. These are standard off-the-shelf systems offered by various suppliers. However, the offer is limited to traditional technologies which has not yet been adapted to stand the increase of sensor number, new sensor locations and the special needs of sensors. As a result, these systems are heavily sub-optimized with no possibility to adapt to local conditions. Figure 3 illustrates the problematic with a nozzle discharging a liquid sheet, breaking into ligaments and droplets. The sheet, ligaments and droplets impact at different locations. The impact zone is made large enough by increasing the liquid pressure upstream. In other words, securing that the critical region is cleaned, at all speeds, and implies wasting a large fraction of the liquid. Figure 2 shows how liquid sprays for wind screen cleaning are influences by aerodynamic forces of the driving car and the complexity of liquid film distribution on the glass and sensor cluster.

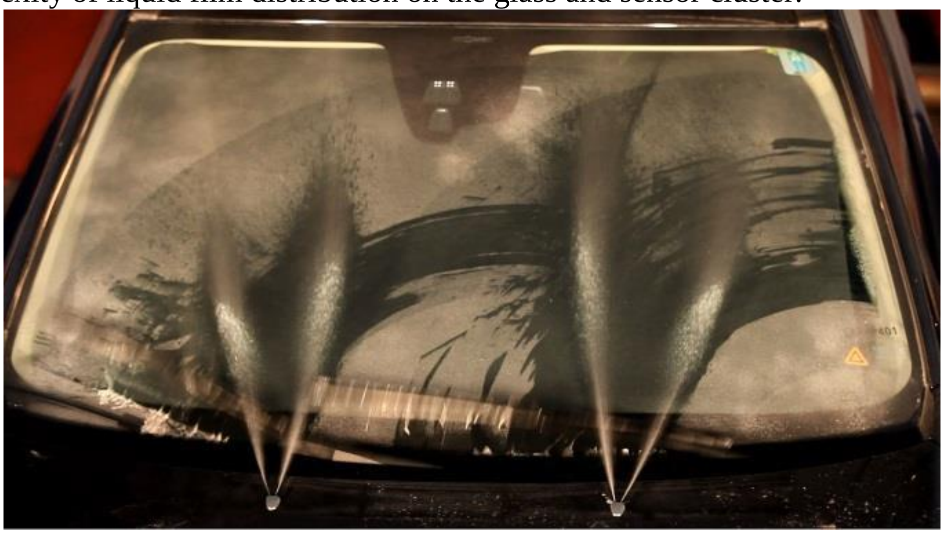

*Figure 2 Wind screen and sensor cluster cleaning at high wind speeds. Full scale wind tunnel tests – Volvo Cars.*

Existing technologies are little optimized for sensor cleaning. In particular, the dynamic conditions of a driving car and changes in liquid properties (due to low temperatures) are not accounted for in the design. Instead, the operating procedure assumes that these factor can be compensated by several consecutive cleaning cycles, increasing further the consumption and emission of cleaning liquid.

This lack of flexibility causes problem in respect to the cleaning performance at different car speeds and is not sustainable because it results in a waste of large amounts of cleaning liquid.

Besides the spray and water film modelling, the key to model cleaning performance is a dirt dissolution model. There is no adequate description of the dissolution of particles (dirt) available at the moment. Approaches similar to the dissolution of salt molecules into a solvent (figure 6) could be applied, but it would be needed to tackle problems such as moisture content and surface activation to model the physics behind dry dirt being dissolved from a surface. Only with such a dirt dissolution model it will be possible to predict the cleaning performance of sprays, wipers or liquid films.

Instead, one needs to work already in earlier design phases in order to improve the design of sensor shape, location and cleaning spray towards an optimized solution which needs less cleaning and uses cleaning liquid efficient. This can only be possible with virtual methods, which are able to reliably predict liquid spray behaviour and dissolution of dirt from different surfaces, before full scale vehicles being produced and road test are possible. As a consequence of modelling tools, it will be possible to predict the performance of a large variety of different nozzle designs and ideas. It will be possible to develop a system at which the cleaning spray will be used depending on the driving condition (i.e. vehicle speed, temperature) and design a self-assessment of sensors to identify the cleaning need independently of a driver.
New virtual models will profit from recent progresses in multi-phase fluid mechanics, fluid structure interaction and DEM modelling of particle adhesion and dissolution. Different nozzle designs can significantly change the spray pattern and be adjusted differently depending on driving condition.

*Figure 3 Side and top view of a conventional nozzle discharging cleaning liquid*

A major limitation in designing new cleaning system is the large variety of conditions. In addition, sensors are spread over the vehicle, forcing to consider a variety of locations, each with specific needs. Traditional methods relying on trial and error with experimental tests are not suitable. Figure 4 presents a typical cleaning test, giving a clear view of the procedure. It is, obviously, not agile enough to allow full parameter exploration to find a variety of optimal nozzle, sensor designs or locations. Instead, this problem should be tackled with alternative methods – retaining the full scale validation only in the very last design phase.

*Figure 4 Full scale Head Lamp Cleaning test for a Volvo XC60, courtesy of Volvo Cars*

In addition to better knowledge of particle adhesion, engineering tools including multi-phase fluid dynamic simulations and virtual design (e.g. figure 2) are today available to handle such problem.

The cooperation between Volvo cars and the department of chemical engineering at Chalmers will make it possible that both sides exchange knowledge and together apply techniques from different scientific disciplines. Chalmers could deliver the technique of DEM modelling for particle adhesion and the surface chemistry knowledge which is needed to model the dissolution of dirt into a carrier liquid (cleaning liquid). This approach might be new in fluid mechanics and especially for the automotive industry, but widely used in pharmaceutical applications. The interdisciplinary cooperation would therefor give Volvo cars access to techniques used in other industries, without having the expertise in-house and without having to start from step one.

*Figure 5 Spray and film for headlamp cleaning system, courtesy of Volvo Cars.*

In previous and ongoing studies Volvo Cars has successfully worked with the development of simplified sprays, wall film models (figure 5) and particle adhesion models for different applications. Based on that experience the strong need for a virtual dirt dissolution model was concluded. The variety of conditions of interest demands a systematic study, defining a clear set of objectives and a selection of flexible systems that can be tailored to meet this set. The combination of modern tools and competence opens avenues to do exactly this, as described in the following.

# 5. Objective

The present project aims to maintain the availability of active safety as well as autonomous drive (AD) systems at all weather conditions.
To do so, virtual modelling tools will be developed with the aim to predict cleaning performance on sensor surfaces. With these tools it will be possible to design the position and shape of exposed sensor surfaces jointly with the cleaning system to guarantee sufficient optical access and efficient usage of cleaning liquid.
The design procedure will be knowledge driven. Starting from world class expertise in fluid mechanics, it will use state-of-the-art tools combining virtual design (high-fidelity simulations and multi-parameter optimization) and judicious physical testing (model and full scale testing). The project will incorporate knowledge and methods from different science fields (multi-phase fluid dynamics, CAE-modelling, surface chemistry, fluid structure interaction). Aiming at finding solutions for improving cleaning systems significantly, the present project adopts innovative methods and mind of work. These methods are developed partly within this project, enabling systematic exploration, short design loops and swift improvements.

The project will generated knowledge and methods, which will be of interest for virtual modelling techniques for many different applications in different industries. The aim of the cleaning performance model is to drive innovation in the design of spray nozzles, surface treatment and optimization of sensor design in early design stages. The project will, as well, contribute to develop new methods to transform the knowledge into innovation and engineering. The philosophy of work will result in developing new competences for systematically handling strongly varying situations. The close collaboration between academia and industry will secure smooth transfer of the new knowledge and competences. The educational aspects include the education of professional with a Postdoc project and coupling with education at master level through project parts which can be conducted as thesis projects.

The project output in term of competence and knowledge will be maximized using SMART project management, namely:
Specific: Virtual tool for cleaning performance to maintain availability of AD sensor system, focus on dirt modelling and optimise spray and liquid distribution technique
Measurable: The goal will be reached for a complete set of relevant operating conditions and tested in full scale conditions at Volvo Cars.
Achievable: the project partners are complementary and contribute with all relevant expertise. It is therefore realistic to combine several state-of-the-art techniques in one single project.
Relevant: the involvement of industry and the wide background of the project manager secure that the results will result in innovations and technical solutions.
Time-bound: careful time planning with clear objectives ensures that the project will proceed according to plan and deliver results as expected.

# 6. Results and deliverables

## 6.1 CFD modelling

For this CFD model simulation development three different wiper system was investigated. The wiper system that are used for simulation development are; wiper system with nozzles spraying from the hood, Jet-wiper, where nozzle are integrated on the wiper arm and Aquablade wipers, which have holes along the wiper bland length. The aerodynamic characteristics of a wiper are influenced by many factors, such as the shape of the wiper and vehicle, rotational frequency and water film covering the wiper and windshield.

To have in consideration of some of the wiper system complexity:

- 3 dimensional
- Two wiper arms/blades with overlapping cleaning area
- Rotational movement of wiper (moving wiper arm)
- Injection of liquid and flow interaction on windscreen
- Curved windscreen
- Injection of water on wiper arm/blades, the hood nozzles
- Flexible wiper blade (to follow the curved screen)
- Flexible wiper blade (to bend the rubber edge at turning point)
- Variation of turning point and wiper speed
- Tension/pressure force from wiper arm towards wiper blade
- Aerodynamic force on wiper blade (dependent on wiper arm position)
- Temperature dependency of liquid viscosity and density
- Rubber friction properties (temperature)
- Temperature dependency of rubber properties

The geometry preparations were made using ANSA developed by Beta CAE Systems. It is important to stress that thorough CAD cleaning and careful meshing is key to having a successful analysis when combining mesh morphing with several advanced physics modules in STAR-CCM+.

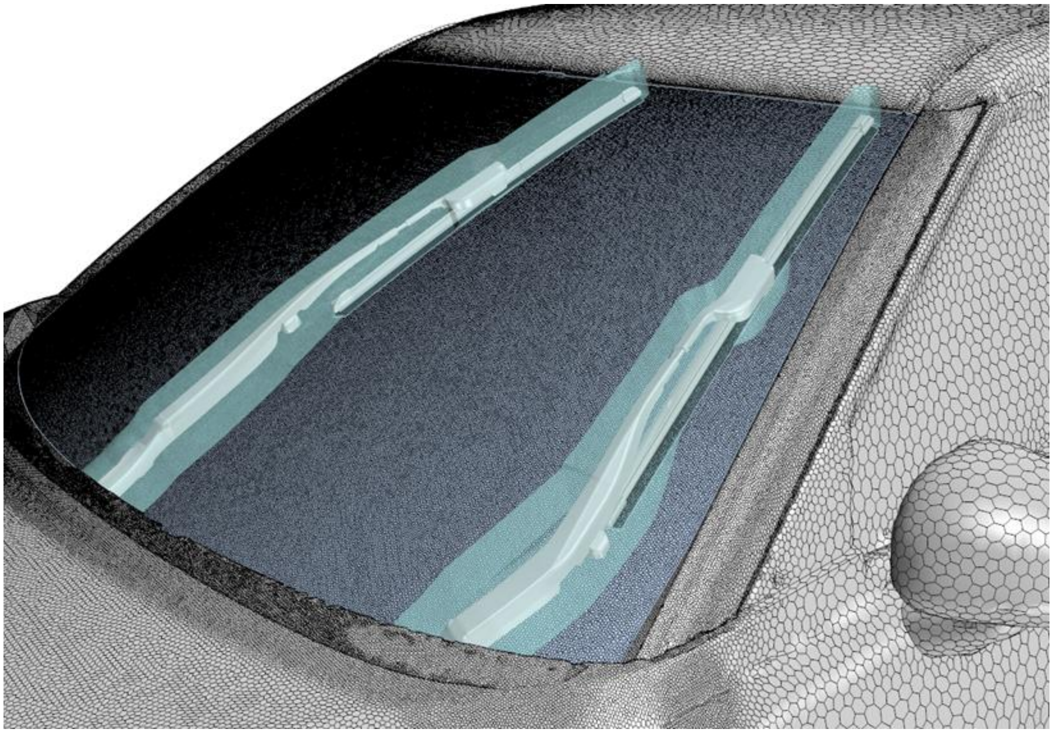

*Figure 6 Front wiper mesh*

The size matching of wiper mesh and the local background mesh by the car window is crucial. To manage the movement of the wiper meshes the overset model of STAR-CCM+ is used. This means that the mesh surrounding the wiper is moved with the wiping motion, and in this case also deformed by the morpher to match the curvature of the window, and then a “hole” is cut in the background mesh where the wiper mesh is inserted in the calculation, by means of interpolation between the meshes in the vicinity of the overset boundaries. Mesh surrounding one of the wipers is illustrated in Figure 7

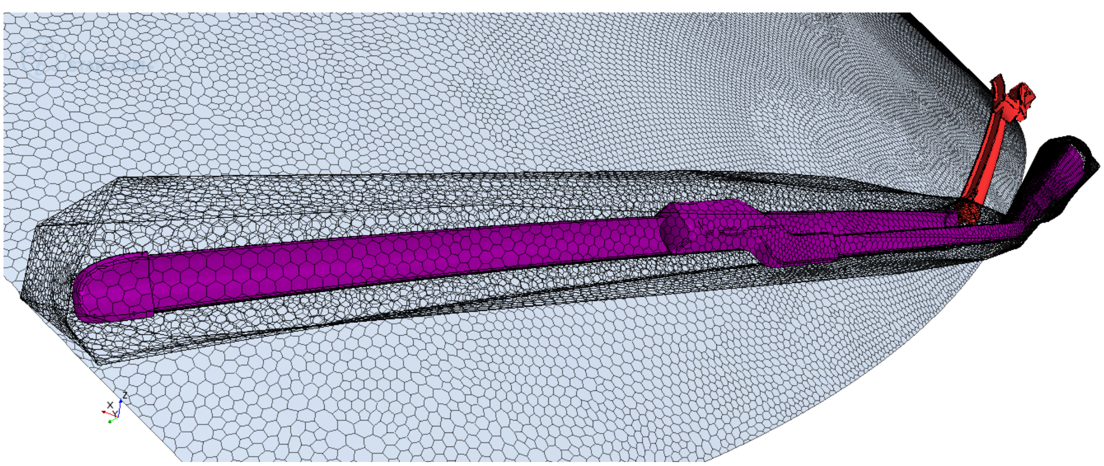

*Figure 7 Wiper mesh*

For the overset hole cut operation to work it is crucial that there is enough overlap between the overset mesh and the background mesh; the recommendation is to have 4 cells of background mesh as well as 4 cells of overset mesh in the overlap region from an internal (wall) boundary in the overset region (such as a wiper arm/blade) and the overset interface (the outer perimeter of the overset mesh). It is also important to keep the prism layers continuous over the interface and avoid retraction when approaching internal structures. Verify this using cut planes through the central regions of the wiper structure.

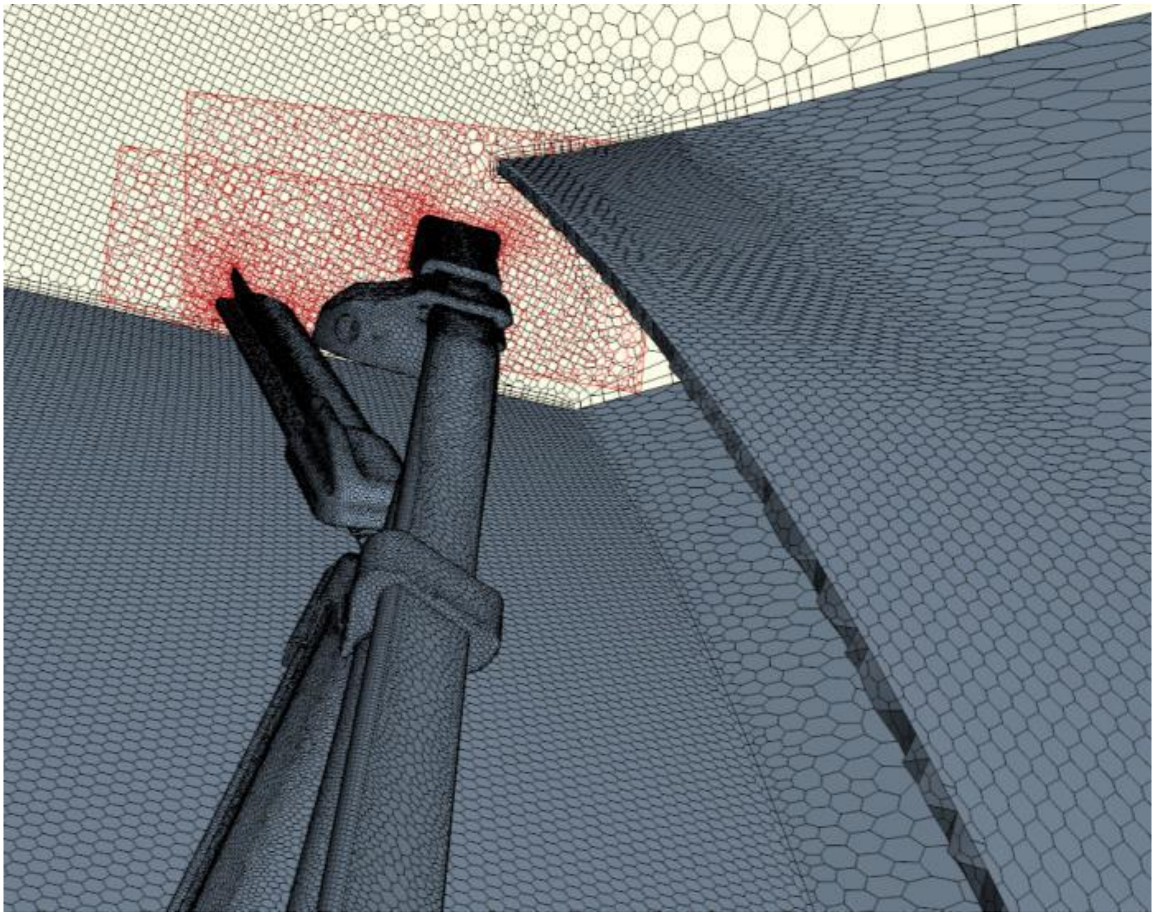

*Figure 8 Overset meshes and background mesh*

The three prism layers on the window are reduced to one layer with thickness of 0.2 mm in other parts of the wiper mesh that is on the wiper arms themselves. Custom conditions were applied on nozzle holes, having target surface size of 0.15 mm and minimum surface size of 0.05 mm.

Given the discussion in section 2.1.5, surface resolution of the wiper rubber structure is a key to a successful mesh. Experimenting with different target and minimum surface size will give a feeling for the trade-off between mesh quality and cell count. More cells increase the computational cost in all steps of a time-step. The major obstacle for decreasing the computational time is the poor scaling. This is primarily caused by moving the wipers, morphing the mesh and the overset interpolation. Target surface size of wiper surfaces are here set to 2.0 mm and minimum to 0.25 mm. Surface curvature value is set to 72 points per circle. By increasing resolution at the surface of the wipers a better morpher robustness is accomplished, at the cost of a higher cell count. Here, the overset meshes was 3.2 million cells each and a mesh of really good quality (all cells > 0.95 face validity, all cells > 1e-3 volume change). Close-up of the improved surface meshing of the wiper rubber in Figure 9.


*Figure 9 Surface mesh on wiper rubber*

Three dimensional aerodynamic CFD simulations were set up and solved using Siemens StarCCM+ software for the CFD simulation development. The wipers are forced to maintain full contact with the window at all times. This is performed by rotating and morphing the wiper meshes using the StarCCM+ boundary condition “slide-on-guide”. Windshield liquid spray is introduced as Lagrangian particle injectors at the locations of the nozzles, with subsequent two-way coupled droplet-air flow.

On the windscreen, wiper liquid thickness is modelled using the fluid film model. In the more advanced setting using Volume of Fluids, liquid film model is still used to handle impact (transition from Lagrangian particles to film) and regions with thin film. Transition from liquid film model to Volume of Fluid is done automatically where the film thickness reaches the height of the first near wall cell.

Air flow is modelled using k-epsilon realizable with all y+ treatment. The realizable was chosen since it is generally more robust compared to for example the SST k-ω. The main model components interacting and interaction models are illustrated in Figure 10 and Figure 11.

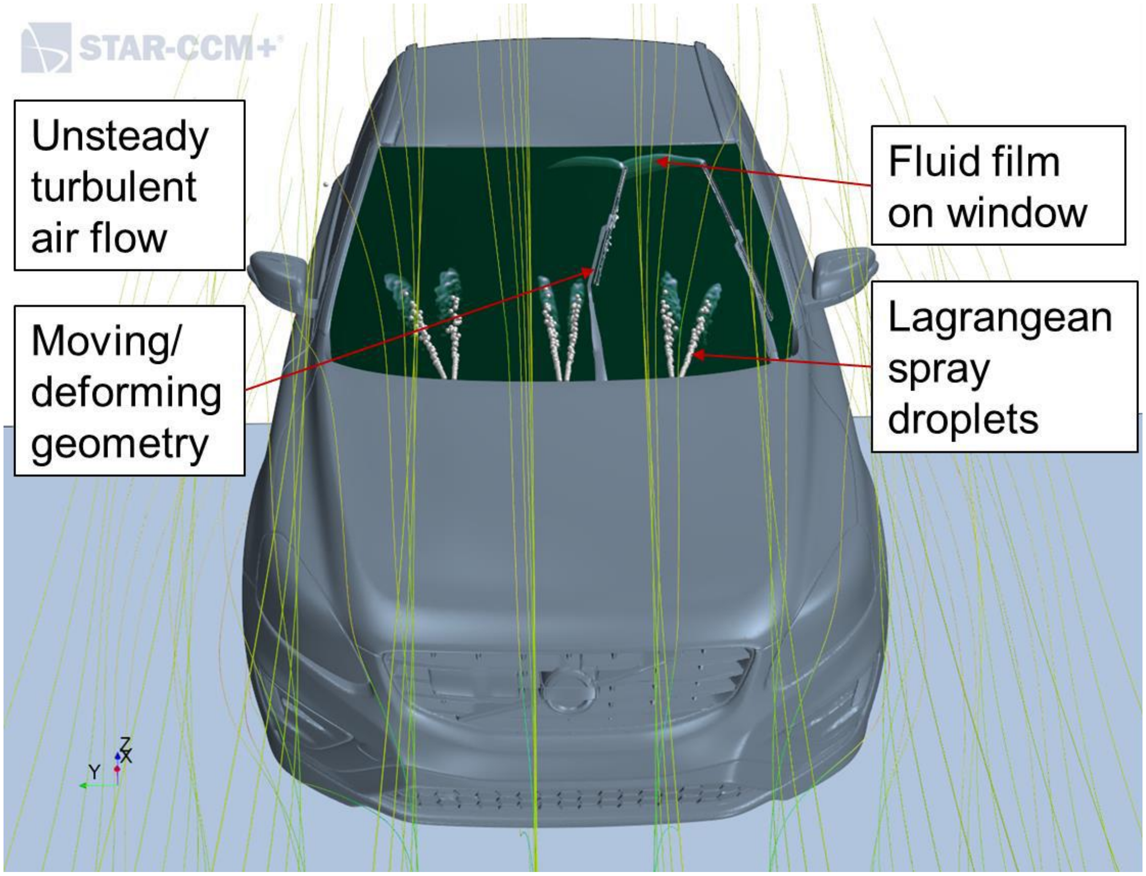


*Figure 10 Model components*

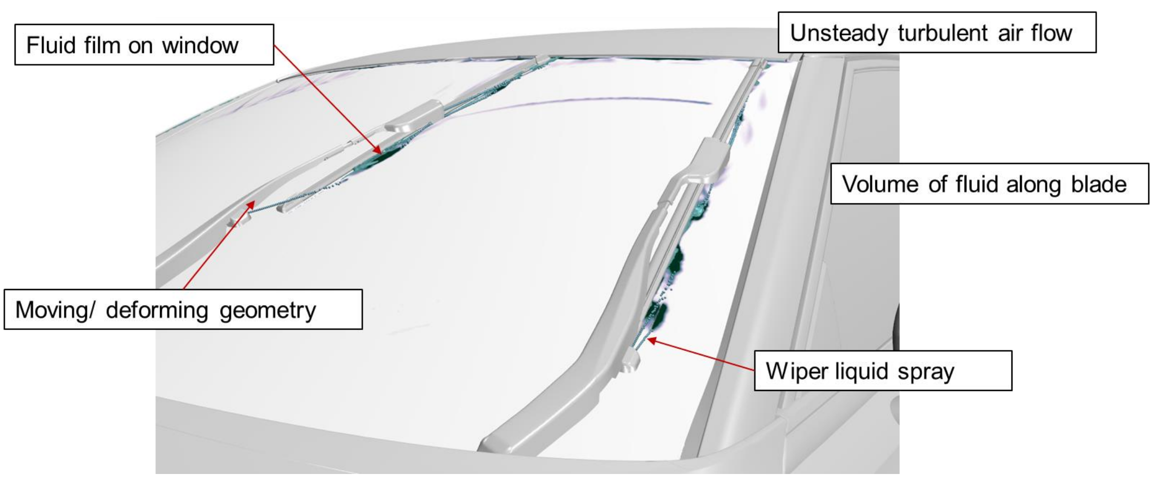


*Figure 11 Model components*

Numerically, three distinct phases are present in the simulation; gas (air) flow past the moving car, Lagrangian spray droplets from the windshield wiper liquid spray nozzles, and fluid film on the windscreen. In this section, interaction between the phases are described

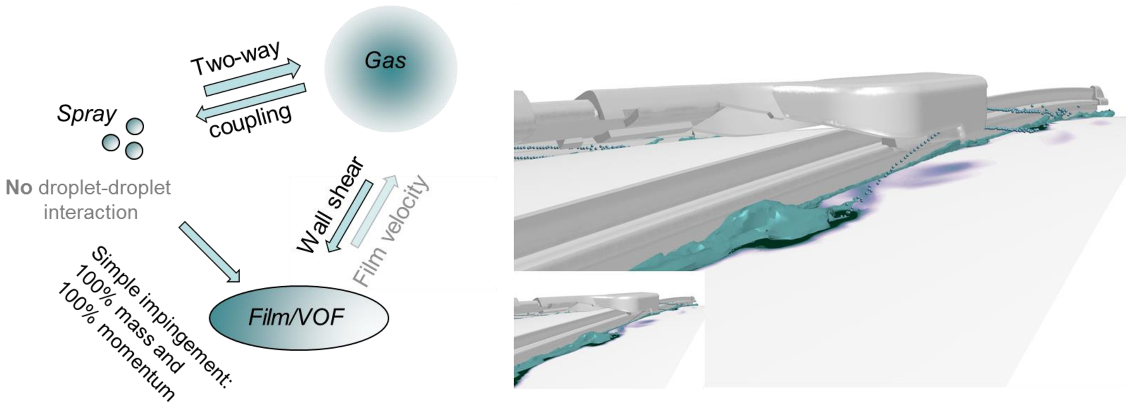


*Figure 12 Interaction models*

To run the CFD model simulation, a work flow has beenproduced with automatated scripts and templates. The CFD model workflow is illustrated below:

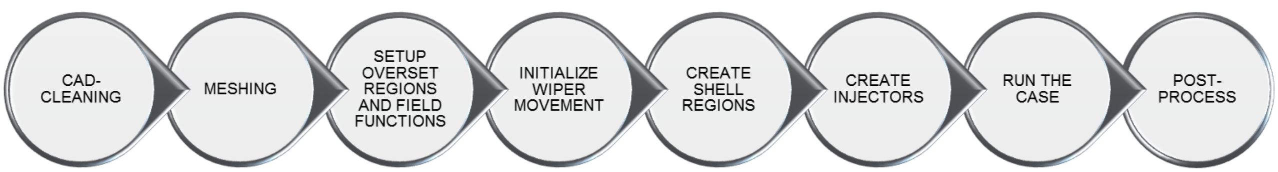


*Figure 13 CFD model workflow*

Below are some post processing of the simulation results which is performed with the developed CFD model.

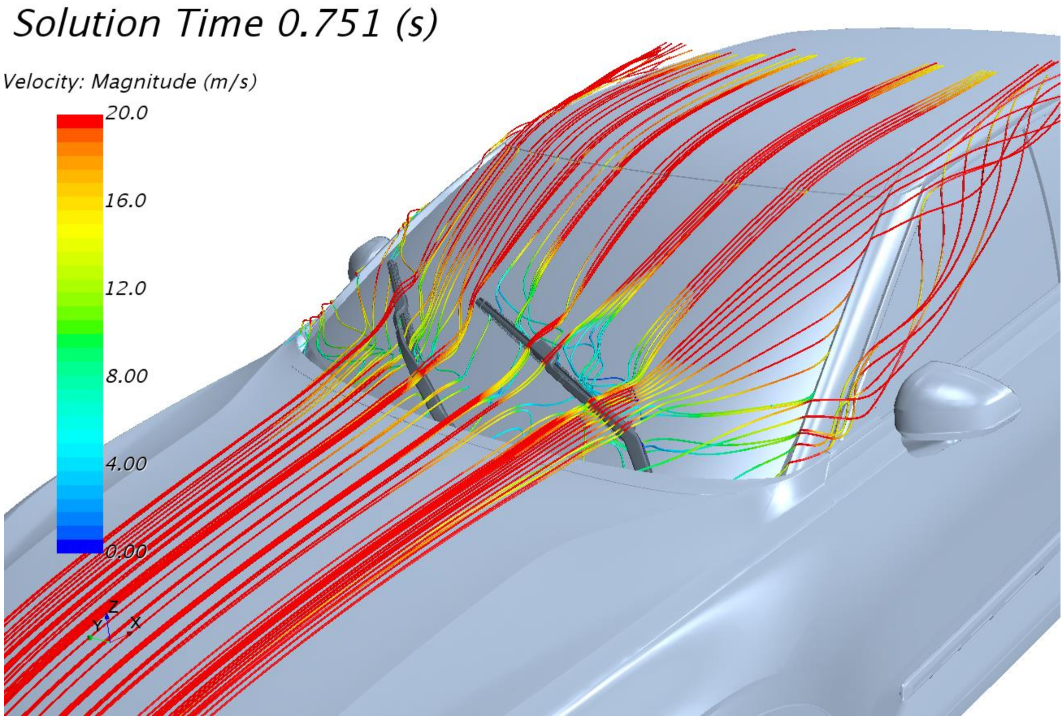


*Figure 14 Streamlines over the wipers*

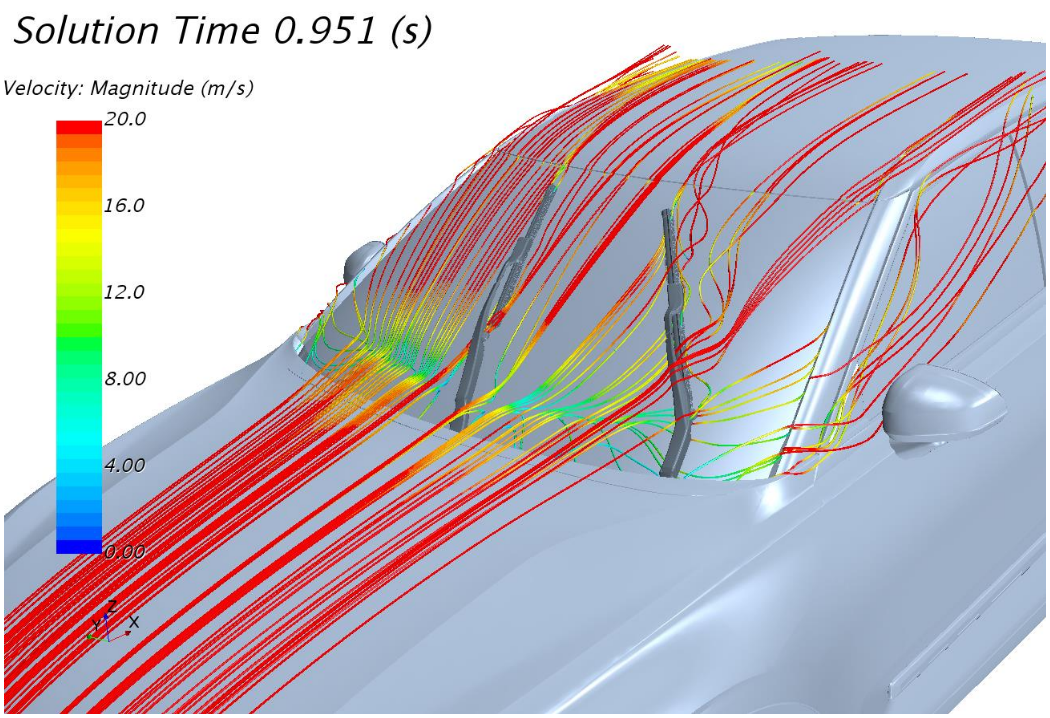


*Figure 15 Streamlines over the wipers in midd-position*

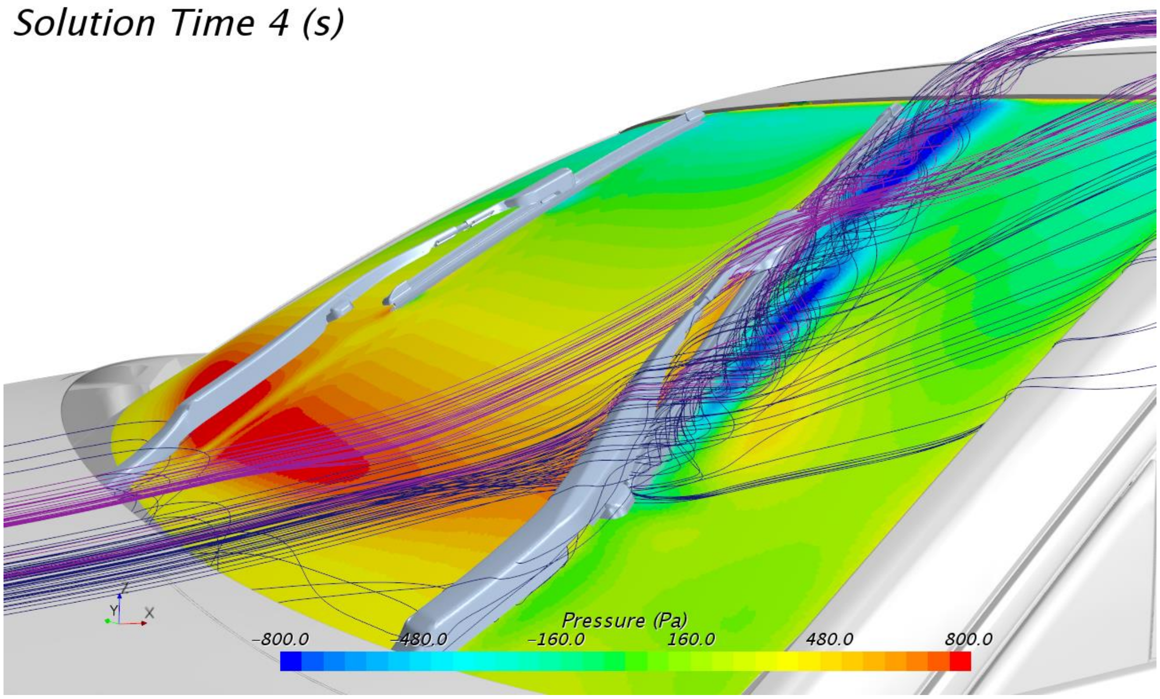


*Figure 16 Streamlines over the wipers*

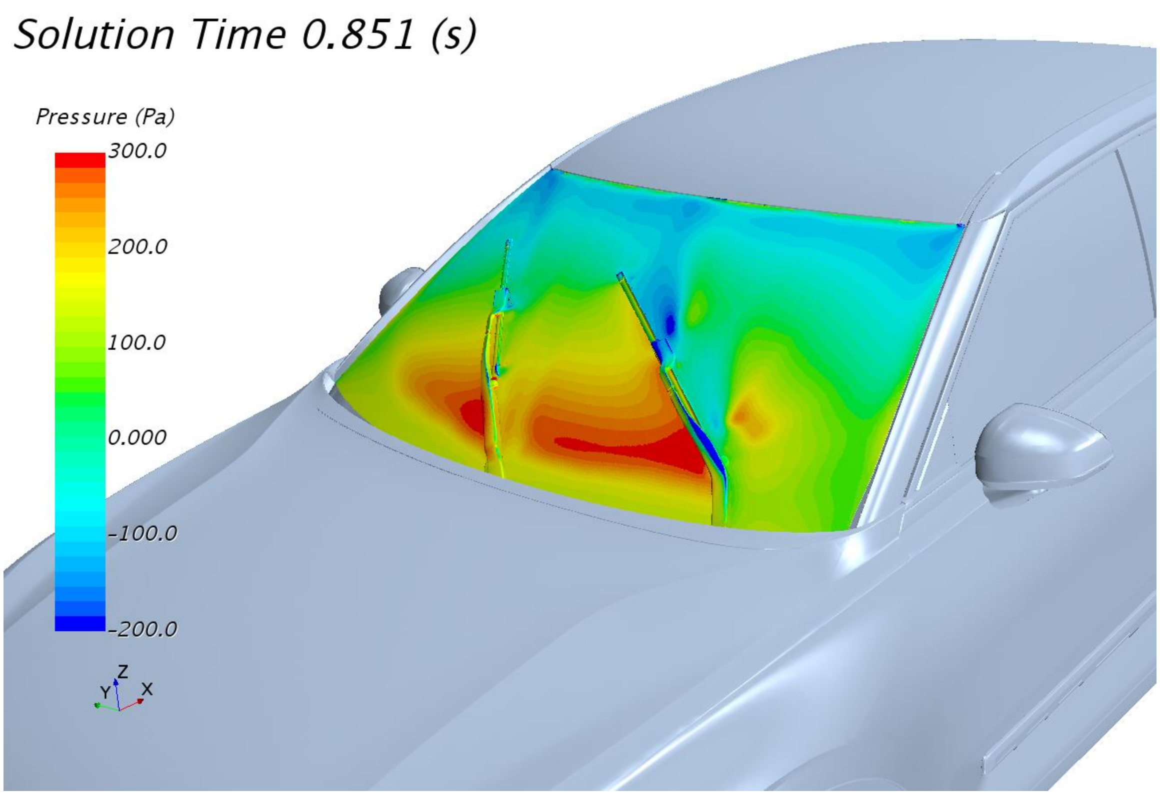


*Figure 17 Pressure field of the wipers and windscreen*

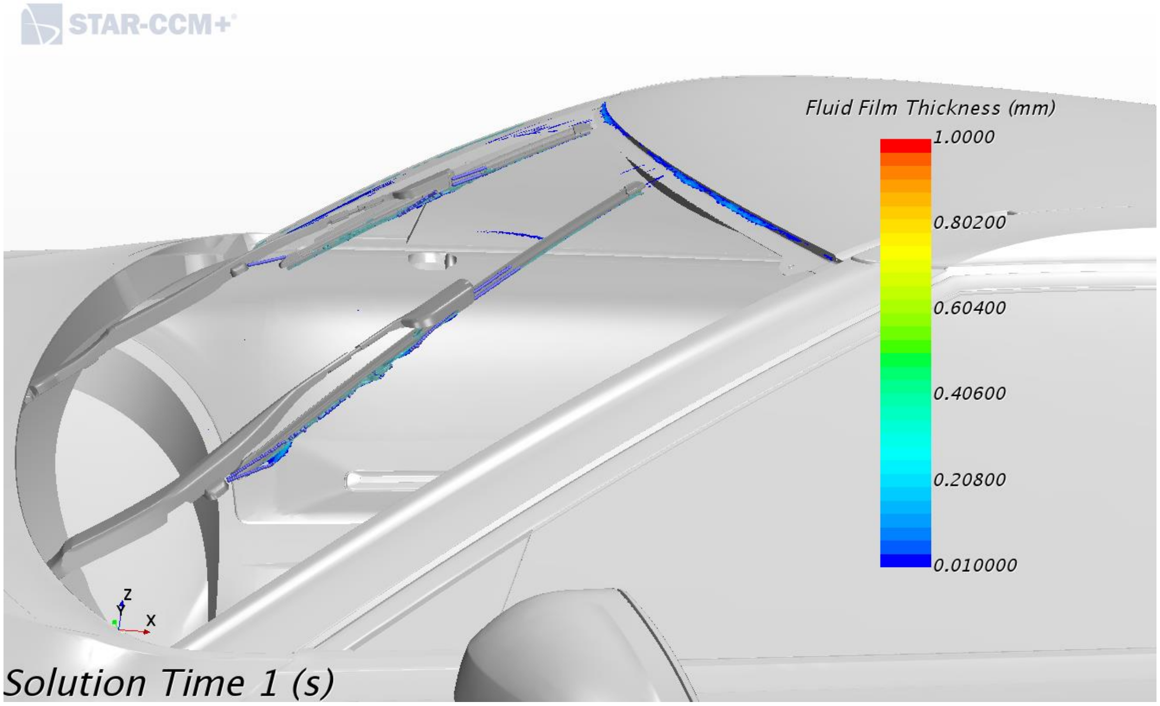

*Figure 18 Water management – wiper wash cycle*

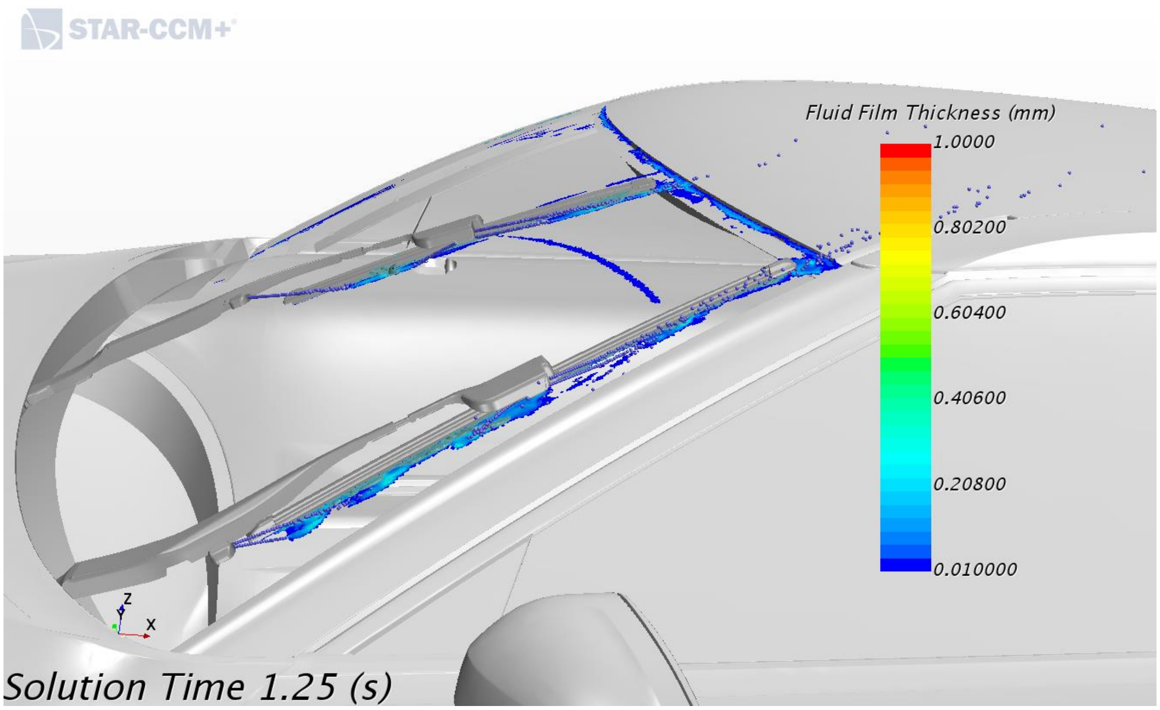

*Figure 19 Water management – wiper wash cycle pull-back*

## 6.2 Dirt dissolution model

To develop the dirt dissolution model the properties of the dirt particle have been studied and investigated through experiments and measurements. The areas that has been researched are summarized and a dirt dissolution model is introduced.

### 6.2.1 A regime map

The normal surface impacts of wet and dry agglomerates are simulated in a discrete element modelling framework. While the impact behaviour of dry agglomerates has been addressed previously, similar studies on wet agglomerate impact are missing. By adding a small amount of liquid to a dry agglomerate, the impact behaviour changes significantly. The impact behaviour of the agglomerates at different moisture contents and impact energies are analysed through postimpact parameters and coupled to their microscopic and macroscopic properties. While increasing the impact energy breaks more inter-particle bonds and intensifies damage and fragmentation, increasing the moisture content is found to provide the agglomerates with higher deformability and resistance against breakage. It is shown that the interplay of the two latter parameters together with the agglomerate structural strength creates various impact scenarios, which are classified into different regimes and addressed with a regime map.

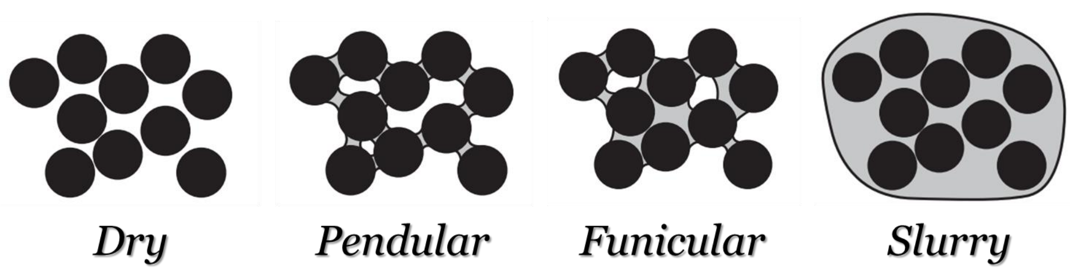


*Figure 20 Particle-Liquid Regimes Liquid regimes in granular material from left to right: dry, pendular, funicular, capillary, and slurry regime.*

Agglomerate strength, liquid content, and impact energy determine the impact behaviour of an agglomerate and its morphology after impact. The effect of binding liquid in the structure of wet agglomerates is significant as it contributes to forming both stronger and more deformable inter-particle bonds. By analysing the damage imposed on an agglomerate during impact and studying post impact parameters, various regimes of impact were characterized based on the severity of the damage and the level of fragmentation. In addition, with dimensionless numbers, the mentioned regimes were mapped against the impact circumstances and the structural characteristics of the agglomerates. It was found that higher impact velocity provided more energy to rupture more bonds whereas greater liquid content facilitated bonds with longer rupture distance, leading to higher flexibility and resistance against breakage. At highly disintegrating impacts, it was noted that, in the very beginning of an impact, an intense shattering leads the system to a maximum population of particles with very small coordination numbers (0–2). This was followed by re-agglomeration of some of the disintegrated particles. The influence of polydispersity was found to be insignificant when an agglomerate is at moderate packing level.

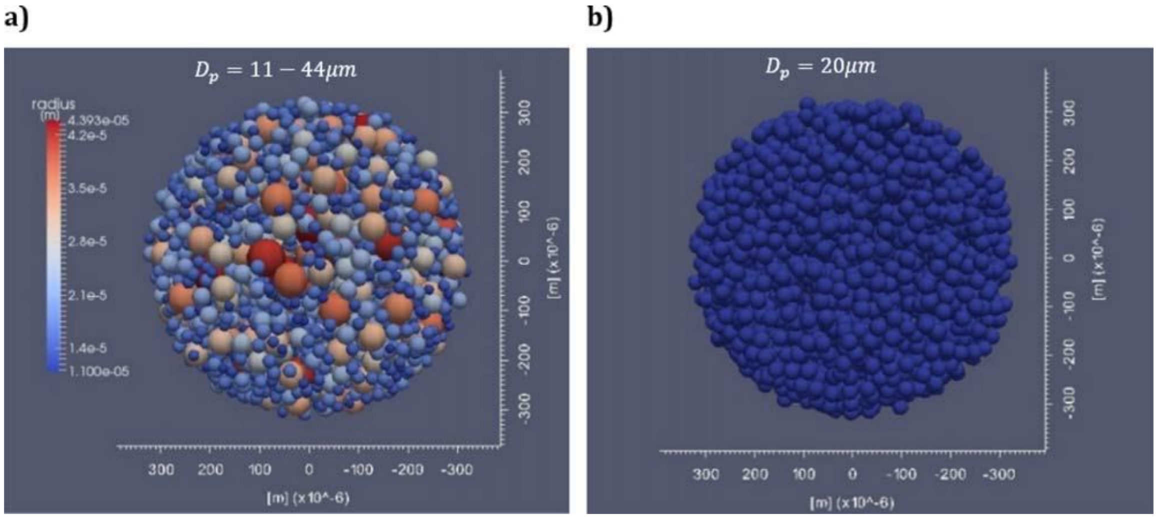


*Figure 21 (a) Polydispersed agglomerate; (b) monosized agglomerate.*

From a mechanistic point of view, the Δ number normalizes the strength of an impact in relation to the strength of the agglomerates. Moreover, the liquid content determines the potential of the system to accommodate and dissipate the sudden impact stress-energy within the pendular regime and prevent the rupturing of inter-particle bonds. Subsequently, the impact behaviour of the agglomerates and the postimpact structure of the agglomerates are classified into four regimes related to the Δ number and the liquid content of the agglomerates. To distinguish these regimes from one another, the borders of each regime must be set. This is done by setting proper criteria on the postimpact behaviour of the agglomerates including the level of deformation (quantified by the aspect ratio (AR) of the deformed agglomerate) and the extent of fragmentation. The criteria assigned to the mentioned parameters are shown in Table 1. The resulting regime map in terms of liquid content and Δ number is shown In Figure 22. It is clear that the dividing line between different regimes is not sharp but gradual. This has been accounted for in Figure 22 with a smooth colour transition from blue to red where blue corresponds to minor deformation (Regime I) and red corresponds disintegration (Regime IV) regimes. The present regime map addresses the coaction of liquid content, agglomerate strength, and impact energy on the severity of the impact and the morphology of the deposited particles.

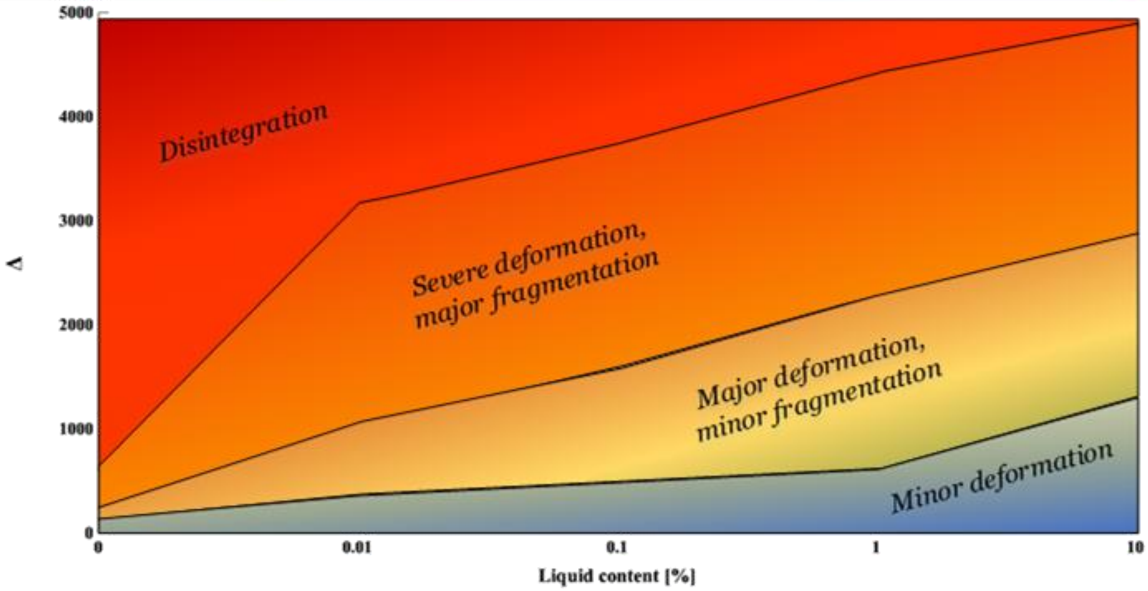


*Figure 22 an impact regime map constructed by the Δ number and the liquid content.*

| Regime | Deformation | Fragmentation |
|---|---|---|
| Minor deformation | Minor ($A_R \geq 0.5$) | Less than 1% |
| Major deformation/minor fragmentation | Major ($A_R < 0.5$) | 1–20% |
| Severe deformation/major fragmentation | Major ($A_R < 0.5$) | 20–50% |
| Disintegration | – | >50% |

*Table 1 the Criteria for Regime Identification*

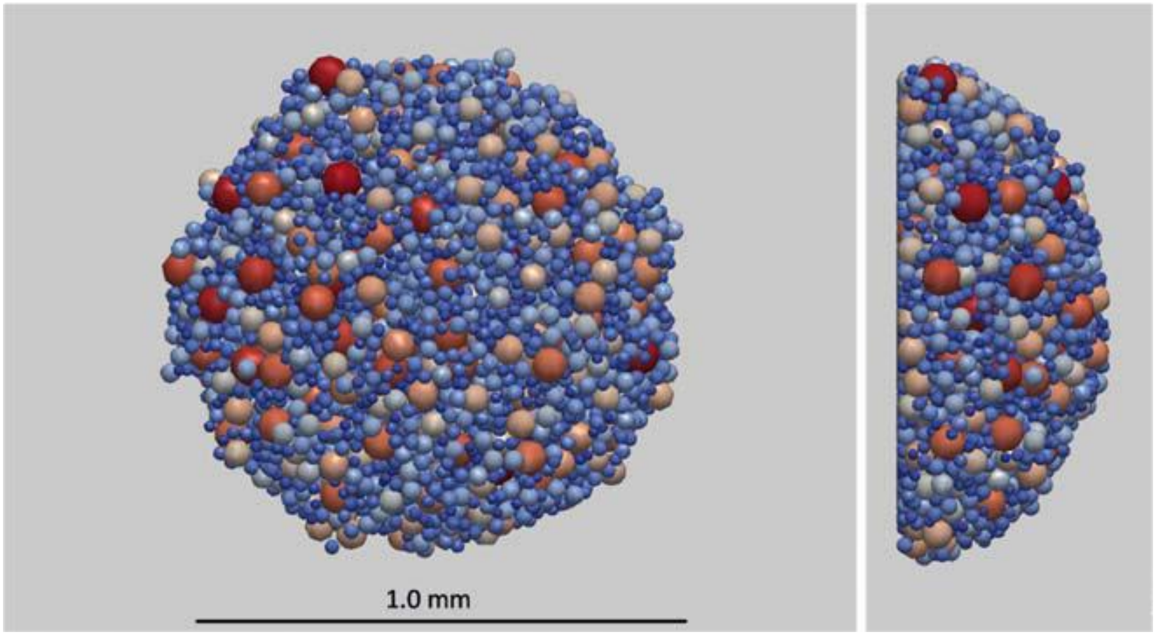

*Figure 23 Minor deformation regime.*

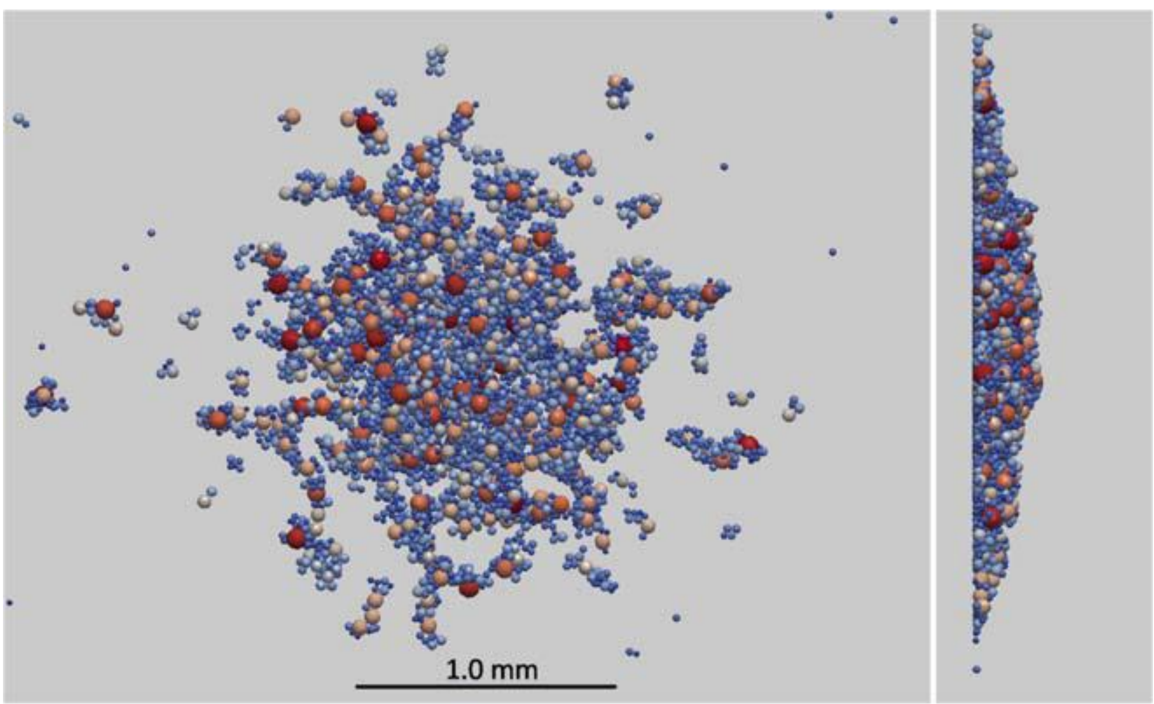

*Figure 24 Major deformation/minor fragmentation regime.*

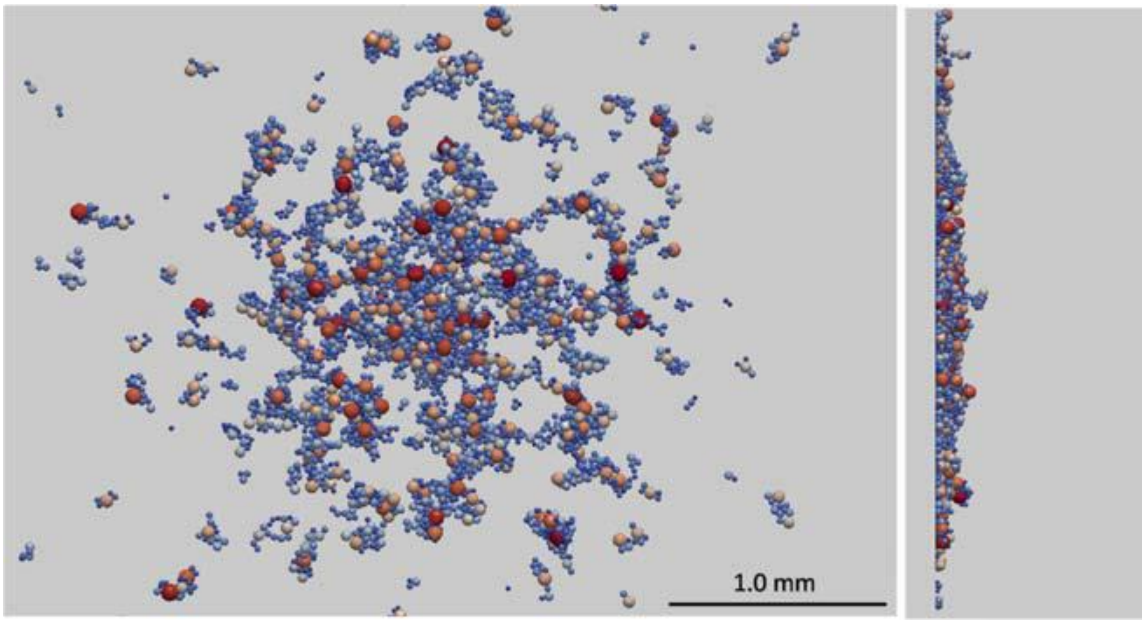


*Figure 25 Severe deformation/major fragmentation regime.*

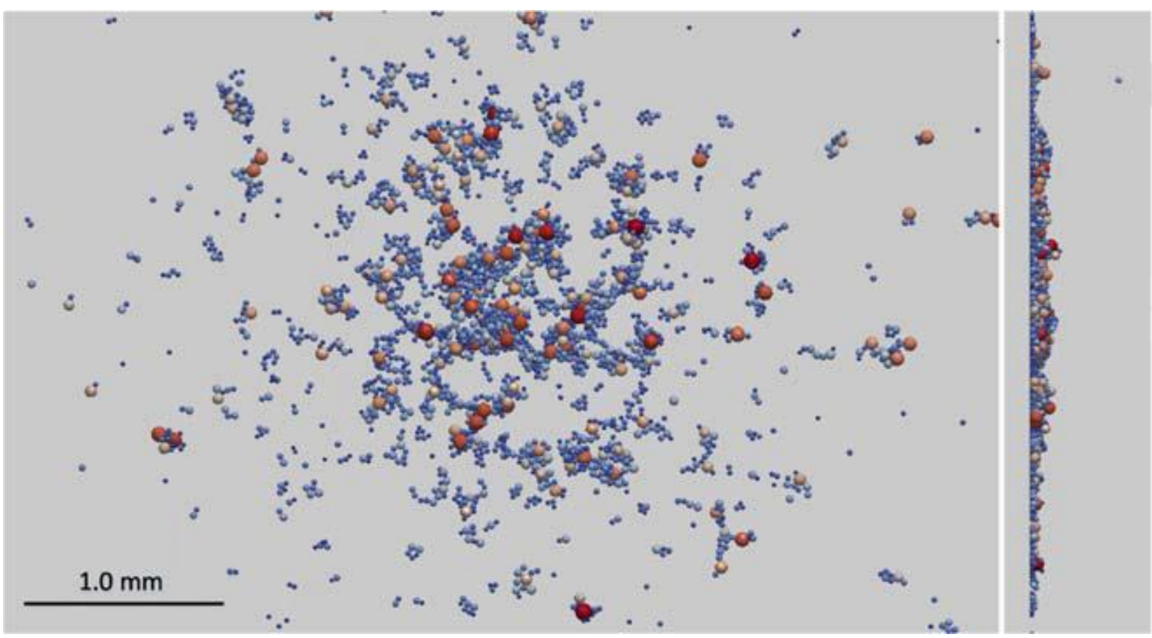


*Figure 26 Disintegration regime.*

### 6.2.2 The morphogy

Through discrete element modelling, we investigate the breakage, deposition and attachment of wet dust agglomerates during normal surface impacts. The morphology and structure of the deposited dirt layer is studied through statistical analysis of the height profiles. it is found that the deposited layer is influenced by both the structural properties of the primary agglomerates and the impact conditions. The roughness of the deposited dirt layer shows a positive correlation to impact velocity and a negative correlation to the agglomerate moisture content. Within the pendular liquid regime the structural strength of the agglomerates shows a strong correlation to the moisture content while at higher moisture content the correlation becomes weaker. It is also observed that for a given impact velocity agglomerates of various sizes show similar deposition patterns. To unify the results for different agglomerate sizes, a dimensionless number for surface density is introduced.

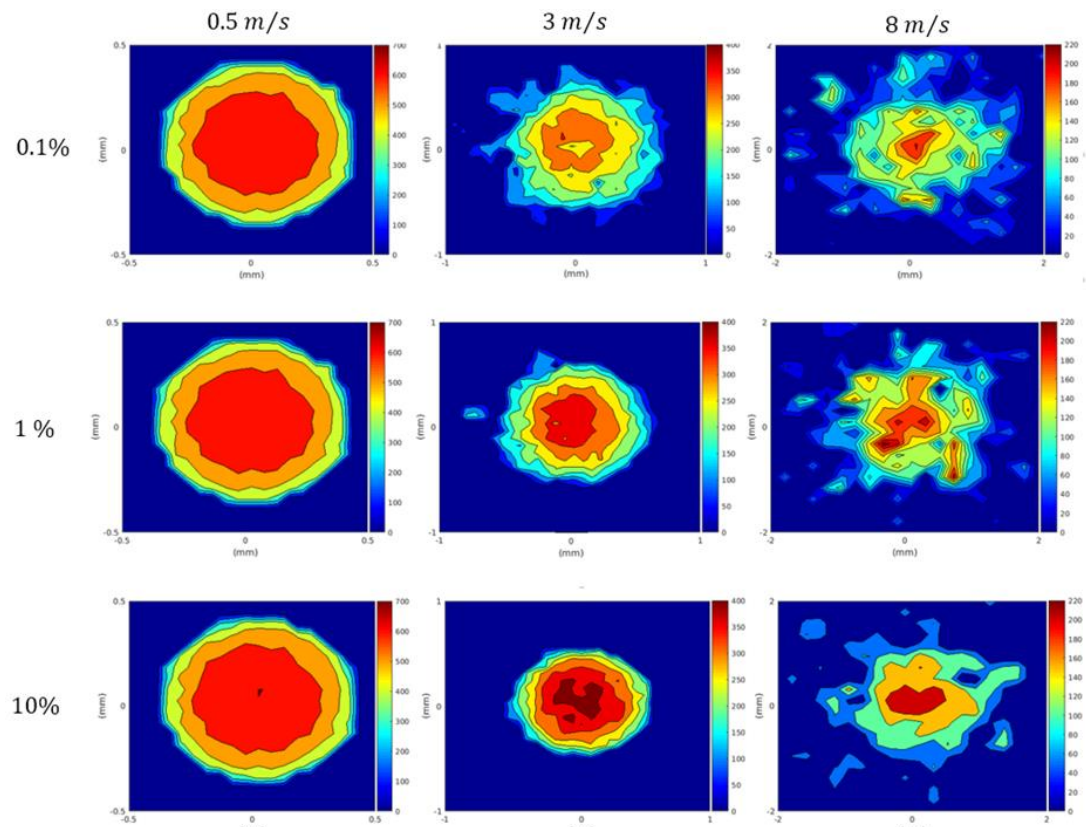


*Figure 27 Height contours of the deposited dirt corresponding to the wet agglomerates at various impact velocities. Please note that the colormap scales and the dimension of the contours are varying with impact velocity*

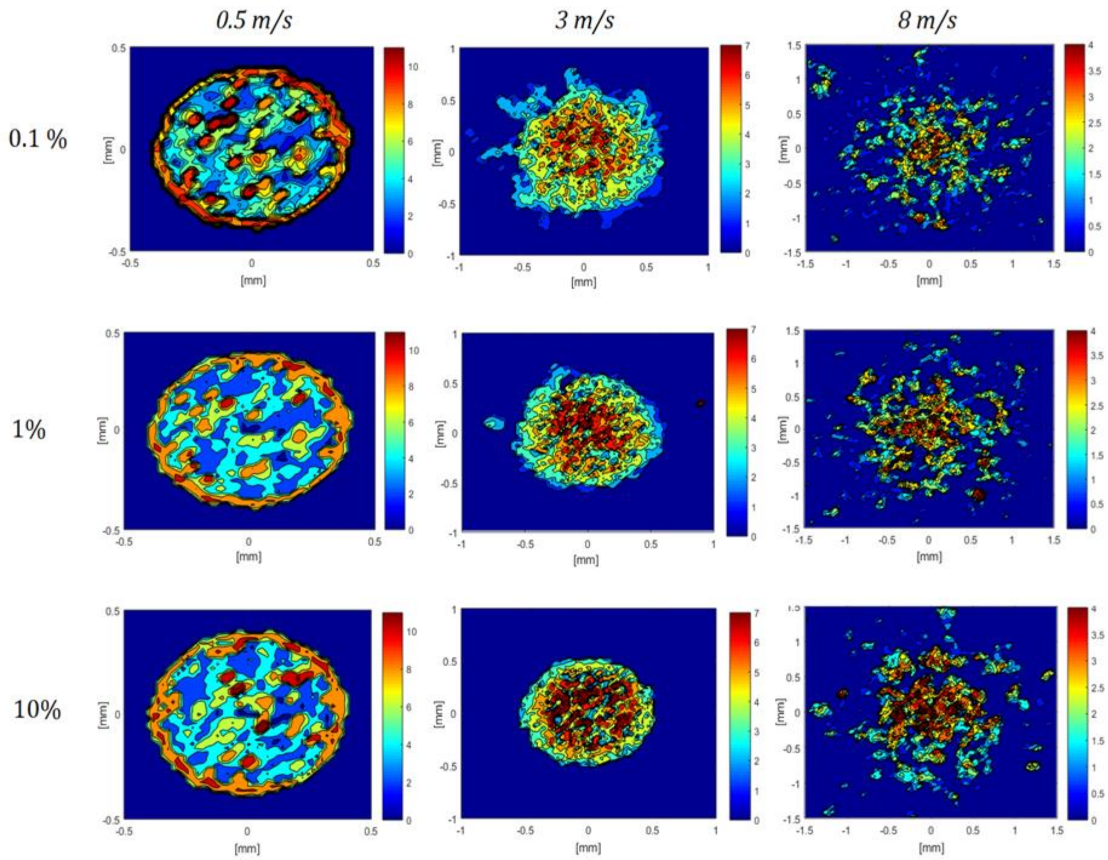


*Figure 28 Local roughness of the deposited dirt corresponding to the wet agglomerates at various impact velocities. Please note that the colour map scales and the dimension of the contours are varying with impact velocity*

The surface impact of an agglomerate leads to deposition and smearing of its constituents over the surface and eventually forming a crust. The morphology and extents of such a crust is affected by a variety of parameters including the agglomerate strength, the agglomerate moisture content and the impact velocity. At low impact velocities, the agglomerate withholds its structure and the crust is mostly of the form of a dome-shaped deposit. Increasing the impact velocity leads to intensified deformation and further to breakage and fragmentation. Within the pendular liquid regime, increasing the moisture content, elongates the required liquid bridge's rupture distance and facilitates the agglomerate with more deformability and higher resistance against breakage. Correspondingly, the transition from mild damage to more severe impact regimes is postponed. At high moisture contents (>10%), where the liquid regime gradually turns into funicular, the agglomerate strength shows much weaker correlation to the moisture content. Depending on the severity of the damage to the primary structure of the agglomerate, the impact can be classified into various impact regimes. It is hypothesized that, for a given impact velocity, agglomerates of various sizes should dimensionlessly show a similar pattern since the ratio between curvature radii of the agglomerate and the wall always equals zero. The hypothesis is verified by numerical experimentation.

### 6.2.3 Incrustation of wet dirt

The macroscopic and microscopic structural patterns formed during the convective drying of aqueous suspensions of dirt (mixture of dust, salt and water) on glass surfaces are investigated. The effects of dust size distribution, convective airflow temperature and velocity on the morphology of the deposited dust aggregates and salt crystals are studied. The critical removal forces necessary to leave behind a clean surface is experimentally determined. Drying at high temperature would cause a strong evaporation rate gradient leading to formation of salt rings and “cauliflower growths”, while drying at low temperature results in large individual crystals. The critical removal forces also correlate to these deposition patterns with the more raised structures requiring the lowest removal force. The strongest adhesive contacts are observed for samples with smoother morphology. The latter usually forms at high level of salt supersaturation (fast drying) in the presence of dust particles

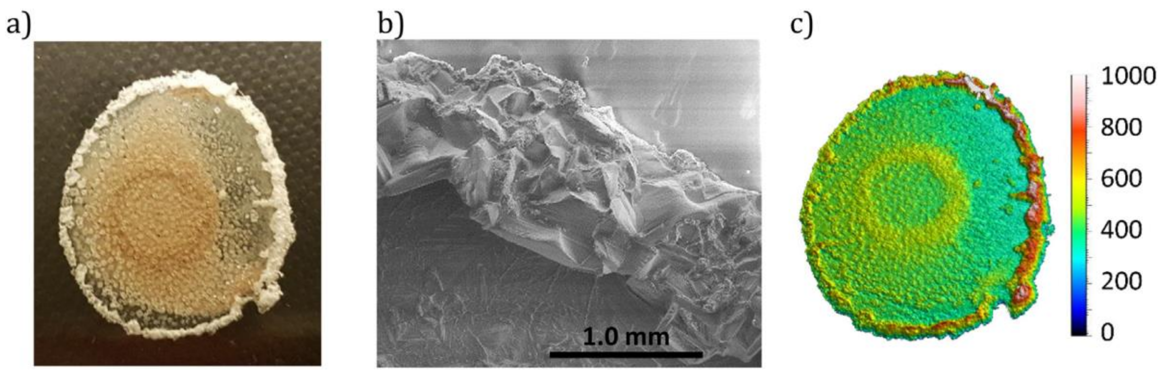


*Figure 29 Salt ring in sample 10 a) photograph b) low magnification SEM c) height profile.*

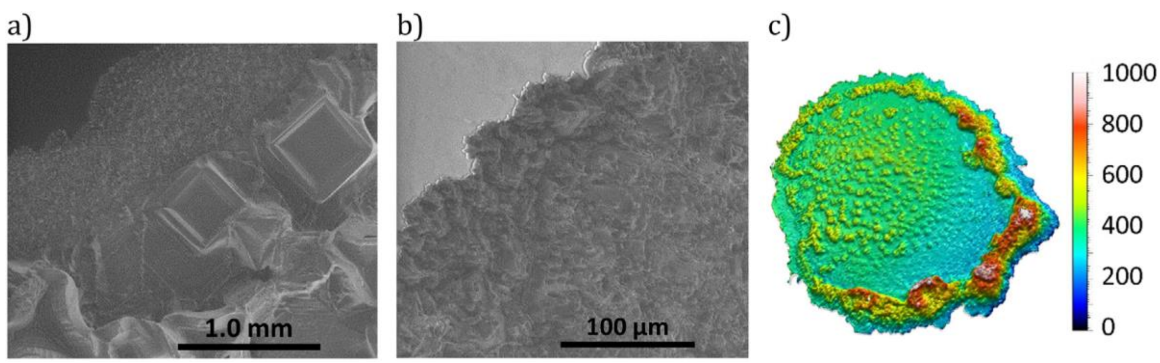


*Figure 30 "Cauliflower growth" regions in sample 6 a) low magnification SEM b) high magnification SEM c) height profile showing flatter outermost region.*

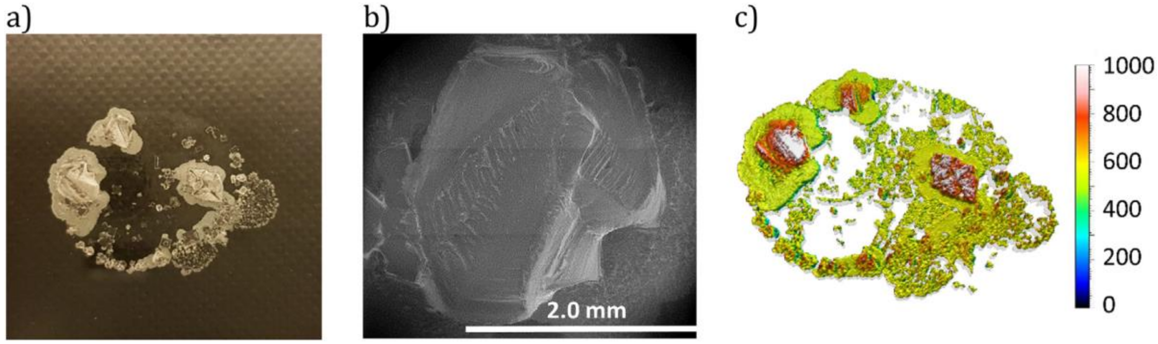

*Figure 31 Large individual salt crystals in sample 4 a) photograph b) low magnification SEM c) height profile.*

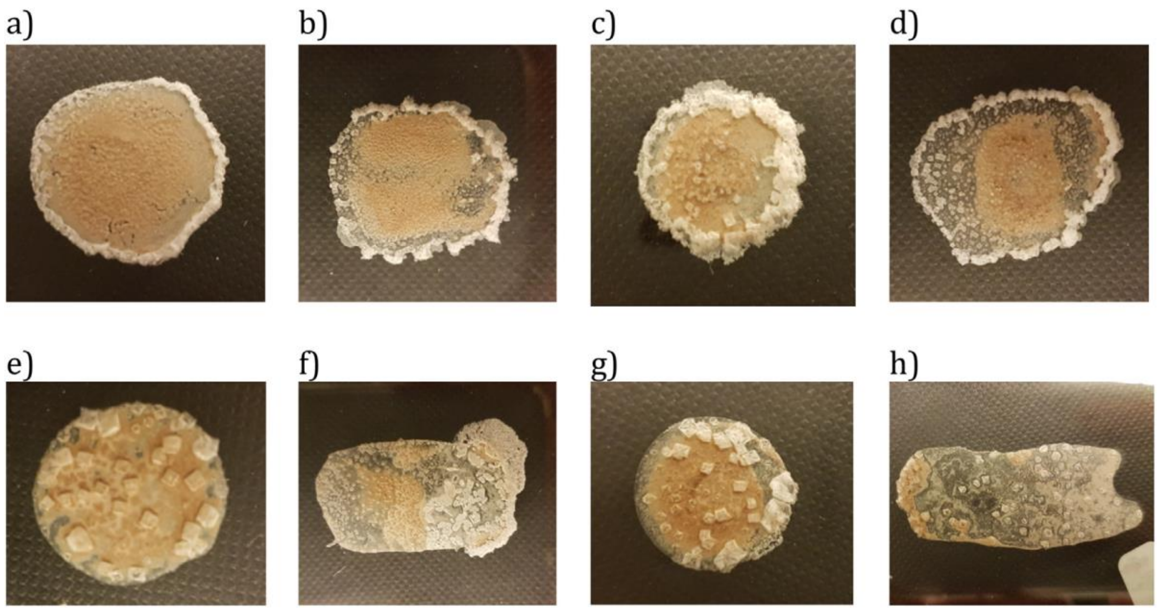

*Figure 32 Effect of spreading a),c) high temperature lowvelocity, samples 6/10 respectively b), d) high temperature high velocity, samples 5/9 respectively e),g) lowtemperature lowvelocity,*

The formation of salt rings, “cauliflower growth” regions and large individual salt crystals present at the edge of the deposits confirms the existence of the outwards internal flow described by the coffee stain effect, at high temperature. At low temperature and high velocity drying, these expected pattern formations are not observed. In this case, the convective air flow surrounding the droplet during drying results in a much more spread deposit since at low temperature the low drying rate makes the droplet more susceptible to influence from the high airflow velocity. This airflow hinders the expected internal fluid flows forming highly spread, flat deposits. The formation of these structures is dependent on the drying conditions and dust grain size. The statistical morphology analysis quantitatively confirms this since the airflow temperature, velocity and dust grain size affect the measured surface parameters.
The dirt removal forces were also found to be dependent on the dirt type and the convective drying conditions. Dust and salt have a synergic effect on the removal

force. The deposits of dust and salt show significantly higher adhesivity compared to dust only or salt only deposits. The dependence of the critical removal force on the convective drying conditions was a result of the different structures formed under these conditions. Increasing the airflow velocity formed more spread deposits which require a higher removal force, while increasing temperature has the opposite effect at the high and low velocities studied. Increasing temperature at high velocity formed more rough structures requiring a lower removal force, while at low velocity, the opposite is observed. The deposits formed with fine dust and salt resulted in the strongest adhesive contacts. The effect of morphology was quantitatively assessed and a negative correlation was observed between mean peak curvature and dirt removal force.

### 6.2.4 The dirt dissolution model

The cleaning of a deposited layer over a substrate is performed through several mechanisms. The mechanism can be pure mechanical like dry scraping or involve a liquid agent to dissolve or disperse the solid deposit from the substrate. These mechanisms can be accompanied with each other or act independently. Dissolution occurs when the deposited solid layer is well-soluble in the liquid agent like the dissolution of salt crystals in water. As for non-dissolvable matters, the cleaning is usually performed through a combination of dispersing and scraping.
Figure 33 show the coupling scheme where the dirt parameters and characteristics are created by the findings through study of particles and agglomerate and through experiments conducted in this project.

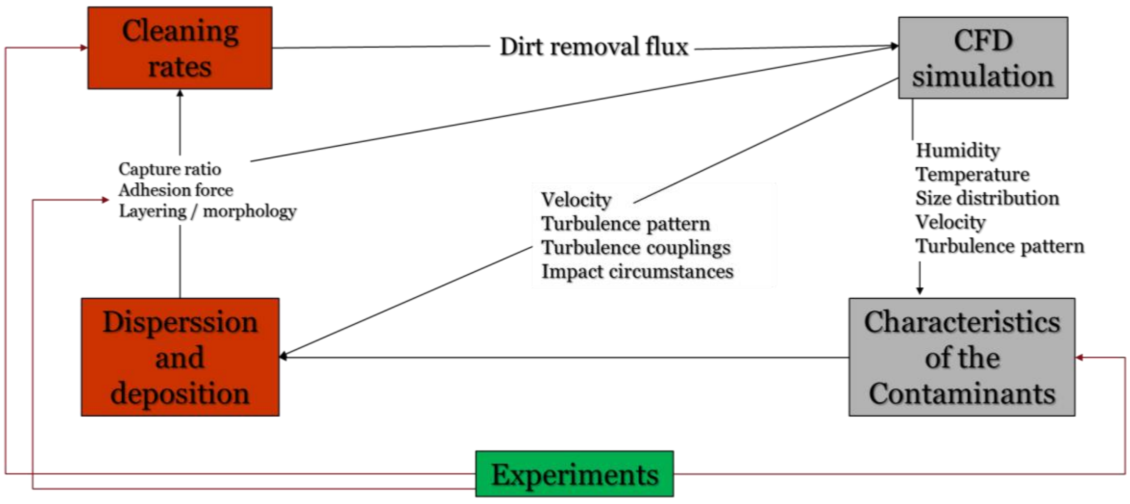


*Figure 33 Coupling scheme to CFD simulations*

A dirt dissolution equation is developed for implementation into CFD model of the wipers simulation. The dirt removal formula is built into the StarCCM+ software as a field function. This is defined as a scraping factor with different threshold representing the different dirt wetness. This ensures that removal will only take place IF a certain threshold value of dirt is reached.

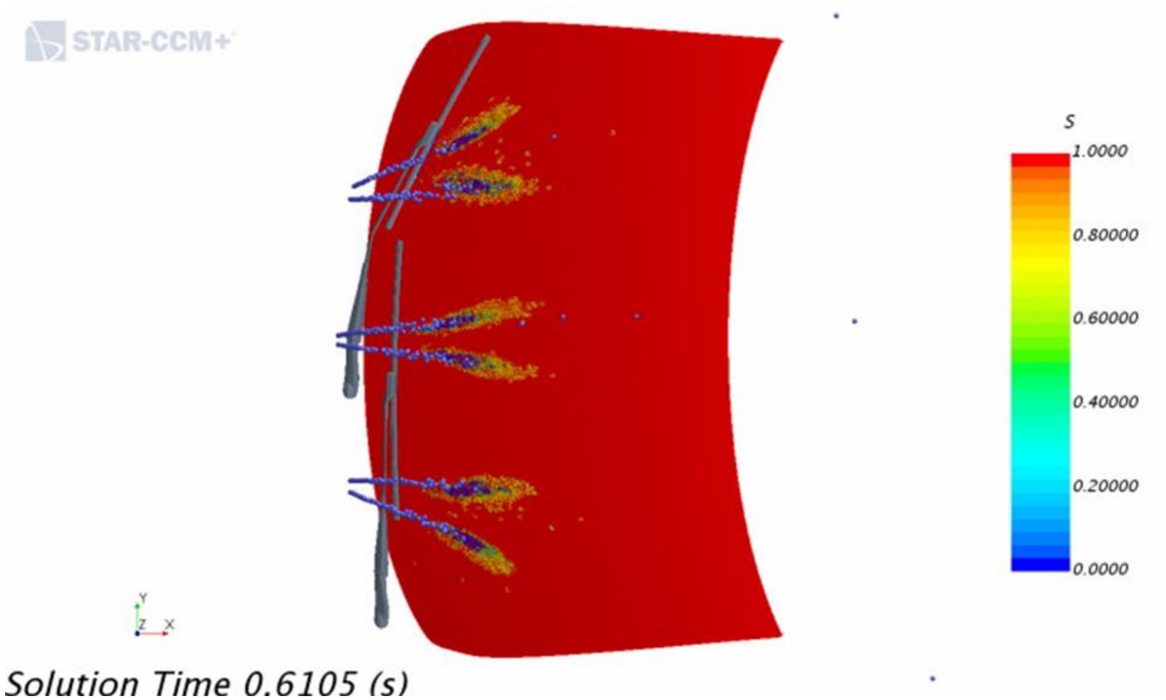


*Figure 34 Example of dirt removal model*

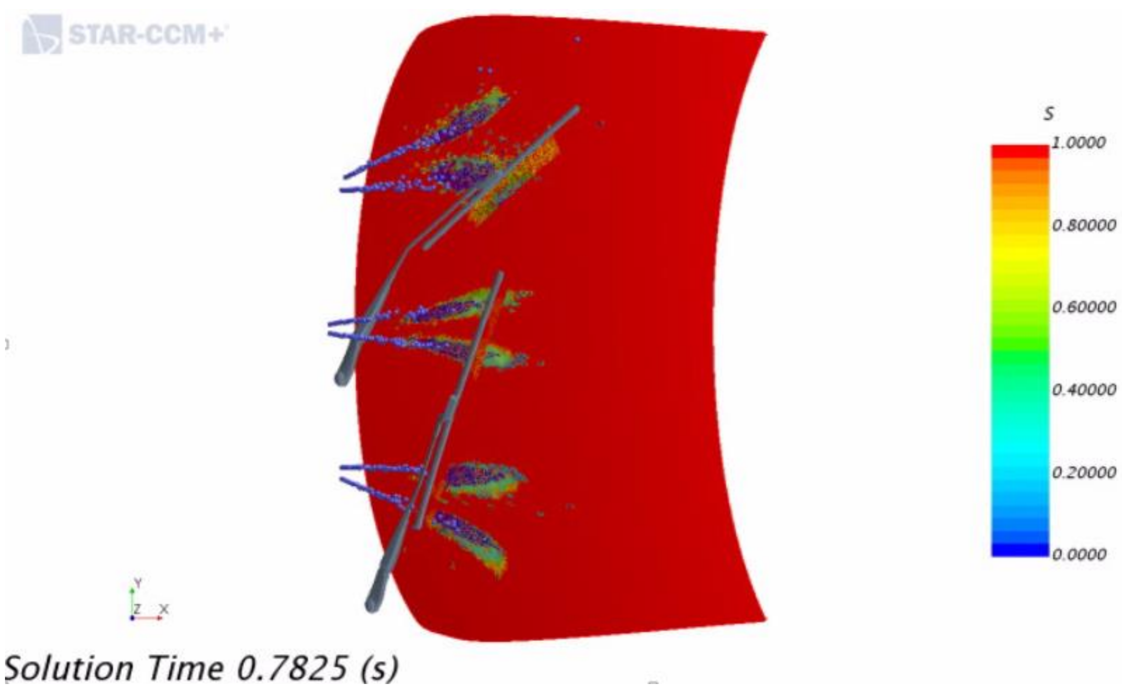


*Figure 35 Example of dirt model*

The formulation of the dirt removal model:

$$d_i(t) = d_0 - \int_0^t dr_1 * dt$$

$$dr_1 = \begin{cases} If\ dr > \mathrm{min}T \ \rightarrow\ dr \\ If\ dr < minT \rightarrow 0 \end{cases} \quad dr = k_1 FFT + k_2 WSS + k_3 Scrape - (k_4 CDD)$$

$d_i(t)$: Current concentration of dirt.
$d_0$: Initial concentration
$dr_1$: Dirt removal rate with logical threshold condition.
$dr$: Dirt removal rate
$minT$: Threshold value at which the removal happens.
$FFT$ = Fluid film thickness / Mass of water
$WSS$ = Wall shear stress
$Scrape$ = Source term where scraping happens.
$CDD$ = concentration of dissolved dirt.
$k_j$= Constants / Variable which weights the importance of each component.

## 6.3 Validation

For validation of the CFD wiper system model, physical tests on complete vehicle with the wiper system were performed to gather data for the simulations. Pressure measurement was done on the wipers over the windscreen in different vehicle speed to get the pressure fields of the wipers and wipers on the windscreen. To measure the pressure of the wipers laying on the windscreen a special pressure pad specifically for wiper profile measurement was used. Figure 36 illustrate the set-up of the pressure pad.


*Figure 36 Wiper pressure pad measurment*

Pressure measurement on the wiper arm was conducted in the Volvo Aerodynamics wind tunnel. The pressure point on the wiper arm Figure 37 was measured in six different wiper position on the windscreen in different vehicle speeds.

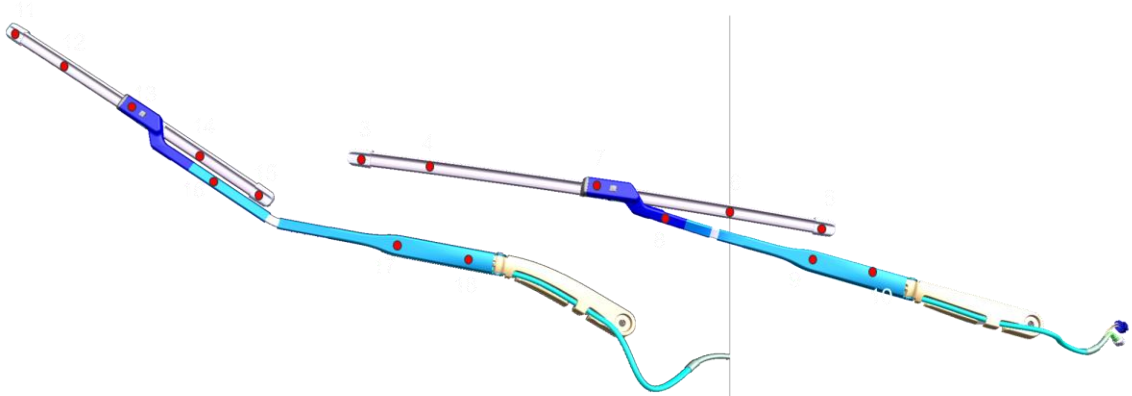

*Figure 37 Pressure poitn measurement on wiper arms*

Wiper washing was recorded with video camera and high speed video camera in test tract with different speeds. This to see the behaviour of the liquid on the windscreen in different speeds. The washer spray was then compared to the CFD wiper system model as shown in Figure 38 and 39.

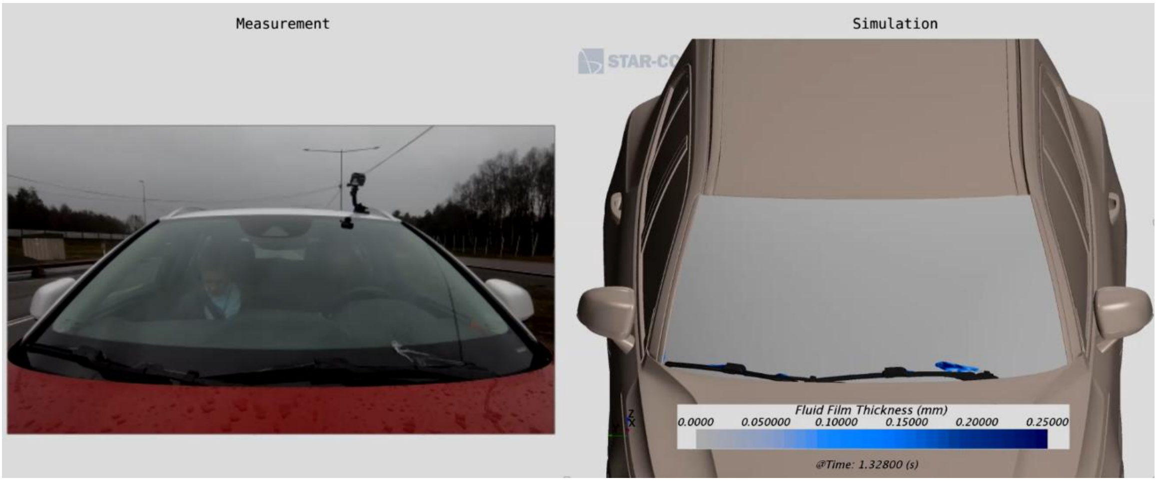


*Figure 38 Washer spray comparison*

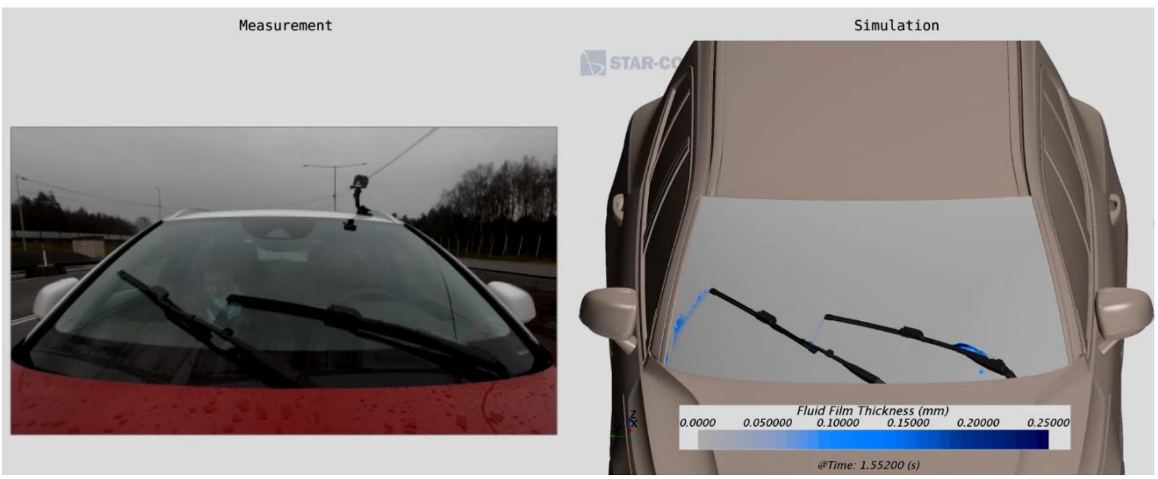


*Figure 39 Washer spray comparison*

The CFD wiper system model show a good correlation with the physical test.

# 7. Dissemination and publications

## 7.1 Dissemination

| | Mark with X | Comment |
|---|---|---|
| Increase knowledge in the field | x | We can now work in the early stage of product development with the wiper, sensor and camera cleaning system which we were not able to do before. This project have also helped us understand the artificial test dirt used to evaluate the wiper cleaning system which we can now advance our test methods. |
| Be passed on to other advanced technological development projects | x | The work conducted to develop the CFD model has supported the software used in this project to advance and optimized the techniques in the software that everyone can benefit from. We are using these techniques to develop and optimize our CFD methods. We are also looking into start a investigation to use the knowledge gain in this project to understand and develop a CFD model for the road dirt which is a very difficult area to investigate. |
| 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 prediction methods developed within that project. |
| Introduced on the market | x | Software techniques |
| Used in investigations / regulatory / licensing / political decisions | | |

## 7.2 Publications

*A Regime Map for the Normal Surface Impact of Wet and Dry Agglomerates*
Mohammad Khalilitehrani, Joakim Olsson, Farin Daryosh, Anders Rasmuson
Journal title: AIChE Journal, June 2018, Volume 64, Issue 6

*The morphology of the deposited particles after a wet agglomerate normal surface impact*
Mohammad Khalilitehrani, Joakim Olsson, Farin Daryosh, Anders Rasmuson
Journal title: Powder Technology, Volume 345, 1 March 2019, Pages 796-803

*Incrustation of wet dirt on glass surfaces through convective drying*
Mohammad Khalilitehrani, Hannah Waters, Farin Daryosh, Anders Rasmuson
Journal title: Powder Technology, Volume 340, December 2018, Pages 173-180

# 8. Conclusions and future research

A three dimensional CFD simulation model was develop in this project. The CFD wiper system model correlated well with the physical test of the wiper performance. The artificial test dirt which is used to evaluate the cleaning performance was studied in this project to find the properties and characteristics of its adhesion and deposition. Through academic research and experiments of the dirt particles and agglomerate a dirt removal model was developed. The dirt removal model is defined as a formula that can be implemented to the CFD wiper system model.
The dirt removal model is not yet mature to replace the physical wiper cleaning performance but can be used for sensor and camera cleaning to optimize the cleaning system for the sensors and cameras. With the CFD wiper system model the vehicle wiper system and sensor and camera cleaning system can be optimized in early stages of product development.

# 9. Participating parties and contact persons

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