IDAJ Conference Online 2023

Robust and Faster Soiling Simulations with Rotating Wheels using iconCFD

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Nov 2023

Agenda

Introduction

- Vehicle rain soiling methodology based on iconCFD V4 was industrially validated
  - Based on 1-way coupling approach
  - Calibration of physical sub-models to reach good level of accuracy
    - Sometimes dependent on specific mesh settings

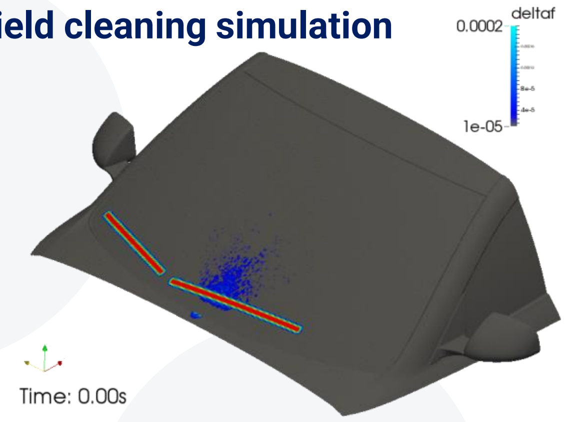
- Known issues in existing soiling methodology
  - Solution instability caused by combination of film source terms and poor mesh quality
  - Stability issue with 2-way coupling
  - Solver slowdown caused by combination of particle tracking and mesh motion

- iconCFD V5 aims to resolve the above critical issues
  - Increased solver robustness and accuracy observed in industrial cases

Key Developments in iconCFD V5

Improved Film Mass Conservation

Animation 1. Windshield cleaning simulation



- The film model formulation and implementation has been revisited
- The film equations are re-formulated using cell fill fraction $\delta = \frac{h}{H}$
  - *H* denotes the height of the single layer extrusion from the surface that forms the film computational mesh
  - *h* is the film thickness
- The implementation of the solver algorithm introduces an improved treatment of gradients, which allows for higher order accuracy
- Film velocity re-normalization is avoided
- Together with careful source term treatment mass conservation is preserved

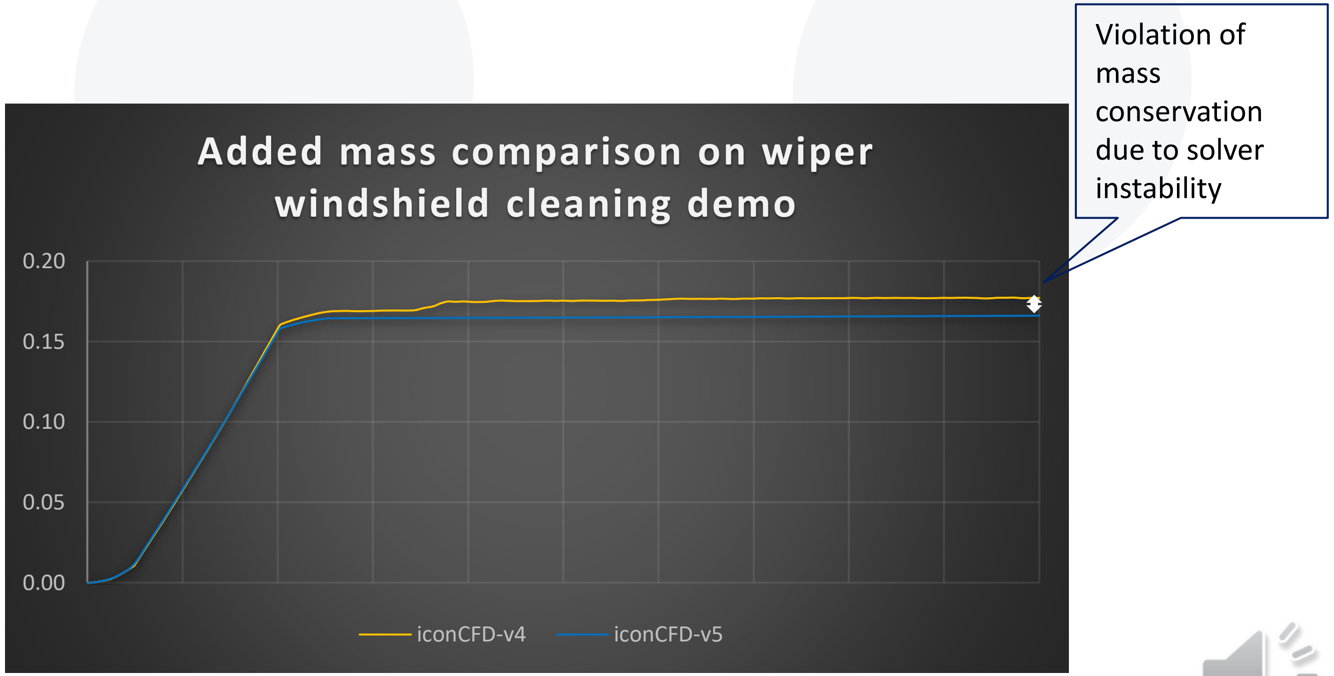


Figure 1. Comparison of mass conservation between legacy and new film formulation

Key Developments in iconCFD V5

Improved Coupling of Air-film Velocity

- The shear force exerted by air onto film is often modelled as an approximation of the shear stress tensor
  - Legacy model is based on the near-wall air velocity
  - Resulting film solution is highly dependent on the choice of the first cell height of the air grid
- This has been addressed in iconCFD V5 with alternative coupling methods:
  - Direct shear-based methods:
    - Shear stress
    - Shear velocity
  - Improved shear stress approximation:
    - Log wind scaling of air velocity
- The latter option allows to tune model parameters on smaller academic cases and apply them to complex industrial geometries
- The former option is more accurate and captures better the air entrainment force

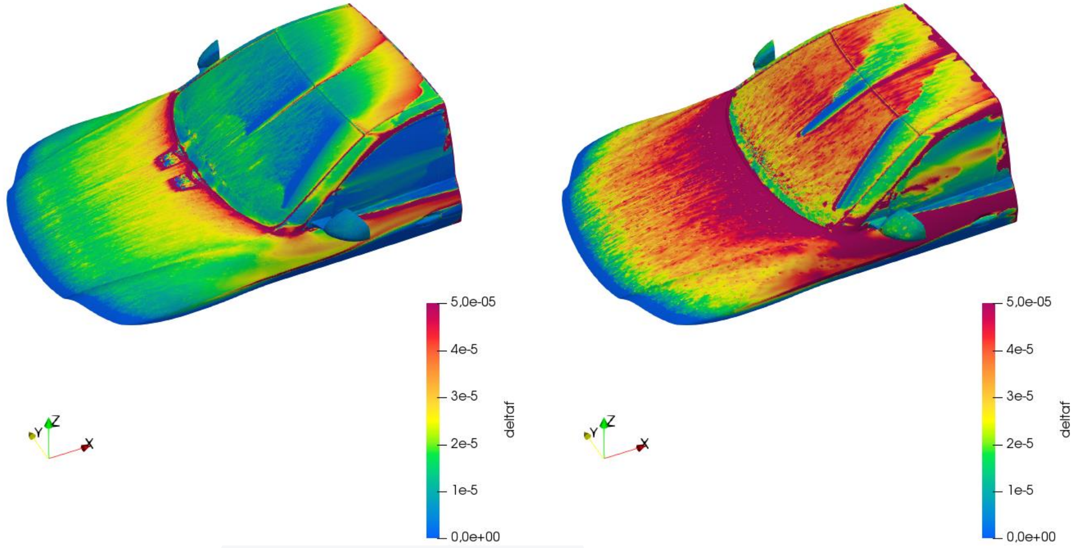


Figure 2. Effect of near-wall first cell height on film solution

Key Developments in iconCFD V5

Improved Modelling of Film Capillary Pressure

- Capillary effects is a term describing the surface tension phenomena occurring at the interface of two fluids
- They have the tendency to minimize the interface curvature
  - For a free droplet in air capillary effects lead to a spherical shape of the liquid
  - For a thin film resting on the surface they attempt to flatten the film top surface as it follows the resting surface
- In thin film, the capillary effects are captured through capillary pressure
- Film curvature is approximated as a laplacian of the film thickness
- This introduces a third-order derivative into the equations
- This third-order derivative presents major finite volume solver stability constraint on the time-step
- iconCFD V5 enables smoothing of this term to minimize spurious currents and unlock higher time-steps with increased solver robustness and accuracy

Animation 2. Illustration of capillary effects

Key Developments in iconCFD V5

Improved Modelling of Film Detachment

- `iconSecondaryDetachment` model enables to specify an arbitrary combination of film detachment models
- A film detachment model defines the mass to be removed from film and injected as lagrangian parcels
- The mass calculation is based either on user definition or physical phenomena causing the parcel ejection
  - Herein, models tend to consider a stability analysis of the film surface
- Following models are available
  - `userInjection` removes mass and introduces droplets where film thickness exceeds user specified threshold
  - `removeInjection` behaves like `userInjection` but the parcel emission is omitted
  - `curvatureSeparation` introduces mass based of instability of film flow over a curved surface
  - `edgeShedding` ejects parcels due to film instability at surface discontinuity
  - `waveStripping` emits parcels due to instability of surface waves in film
  - `brunInjection` yield parcels in areas where gravity overcomes the surface tension

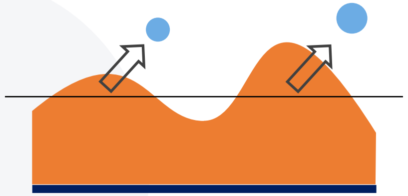


Figure 3. userInjection

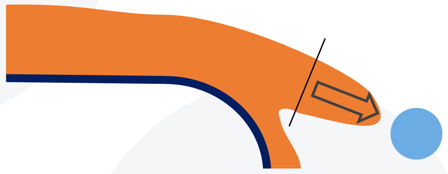


Figure 4. curvatureSeparation

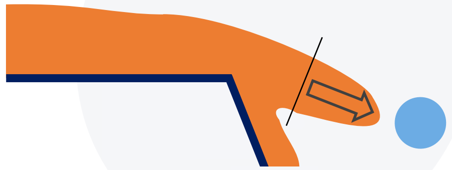


Figure 5. edgeShedding

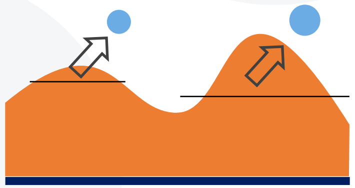


Figure 6. waveStripping

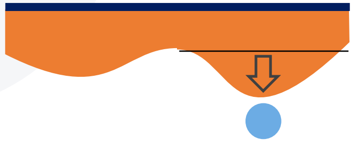


Figure 7. brunDripping

Key Developments in iconCFD V5

Other Numerical Enhancements

- Droplet deposition on the studied surface introduce mass into the film
  - On highly refined industrial meshes this can commence instability if a small face receives large droplet
  - In such scenario, Lagrangian sources are spread to the surrounding faces in order to improve stability
- Primary air-film explicit pressure coupling can induce a film solver divergence
  - This can be avoided with explicit pressure bounding for marginally stable primary air solutions
- For large time-steps, film thickness lower bounding can affect mass conservation
  - The trimmed mass in thickness predictor is appropriately returned in momentum corrector in order maintain mass conservation
- Courant number evaluation has been extended to capture the remaining stability concerns
  - Formerly, only convection limit has been evaluated
  - Current implementation scopes the film equation as a whole
- Gradient and diffusion terms can now support second order numerical schemes
- Capillary pressure smoothing has been enhanced to support larger time-steps

Key Developments in iconCFD V5

Validation Cases

- The compounding effect of the presented improvements can be observed on the example of the rivulet panel case

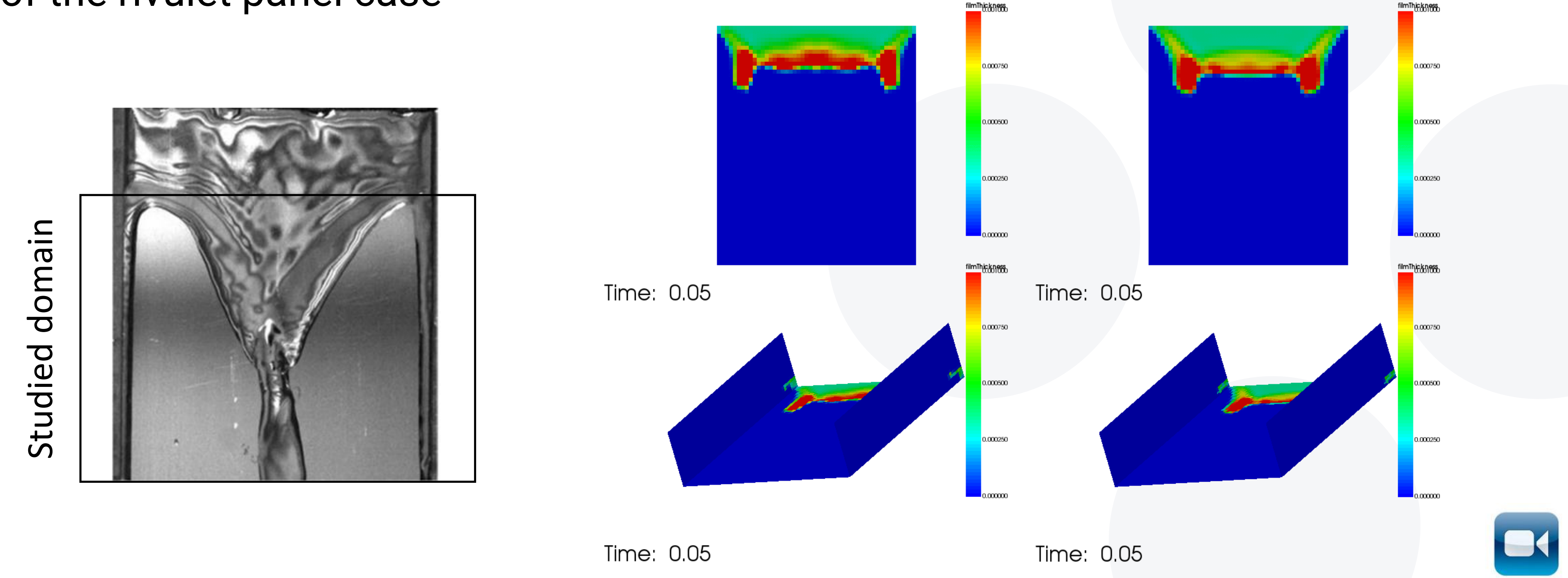
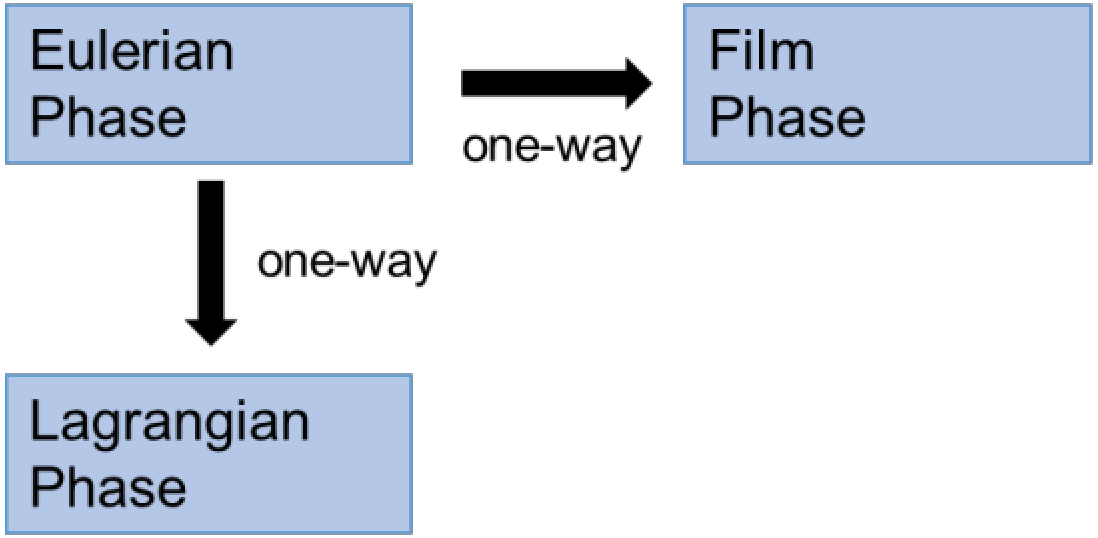


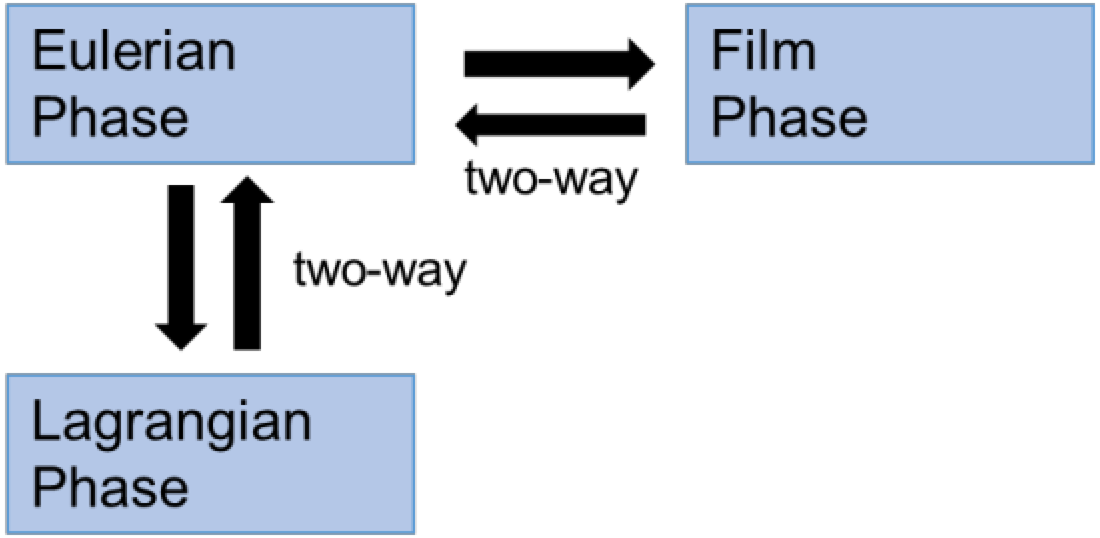
Figure 8. Qualitative comparison between experiment [1], legacy and new implementation for water flow on a $60°$ inclined polished steel plate at $Re = 162$

[1] A. Hoffmann et all, Detailed Investigation of Multiphase (Gas–Liquid and Gas–Liquid–Liquid) Flow Behaviour on Inclined Plates, Chemical Engineering Research and Design, Volume 84, Issue 2, 2006, Pages 147-154, ISSN 0263-8762, https://doi.org/10.1205/cherd.05110.

Vehicle Soiling Methodology

1-way vs 2-way Coupling





- Airflow is not affected by particles nor film
- Assumption of frozen or transient airflow
- Time-efficient methodology suitable for air-driven film flows:
  - A-pillar or side window overflow

- Full transient approach
- Airflow is affected by particles mainly
- CPU-expensive but accurate method for surfaces exposed to lower air speed and direct particles impacts:
  - Side mirror contamination

Vehicle Soiling Methodology

1-way vs 2-way Coupling

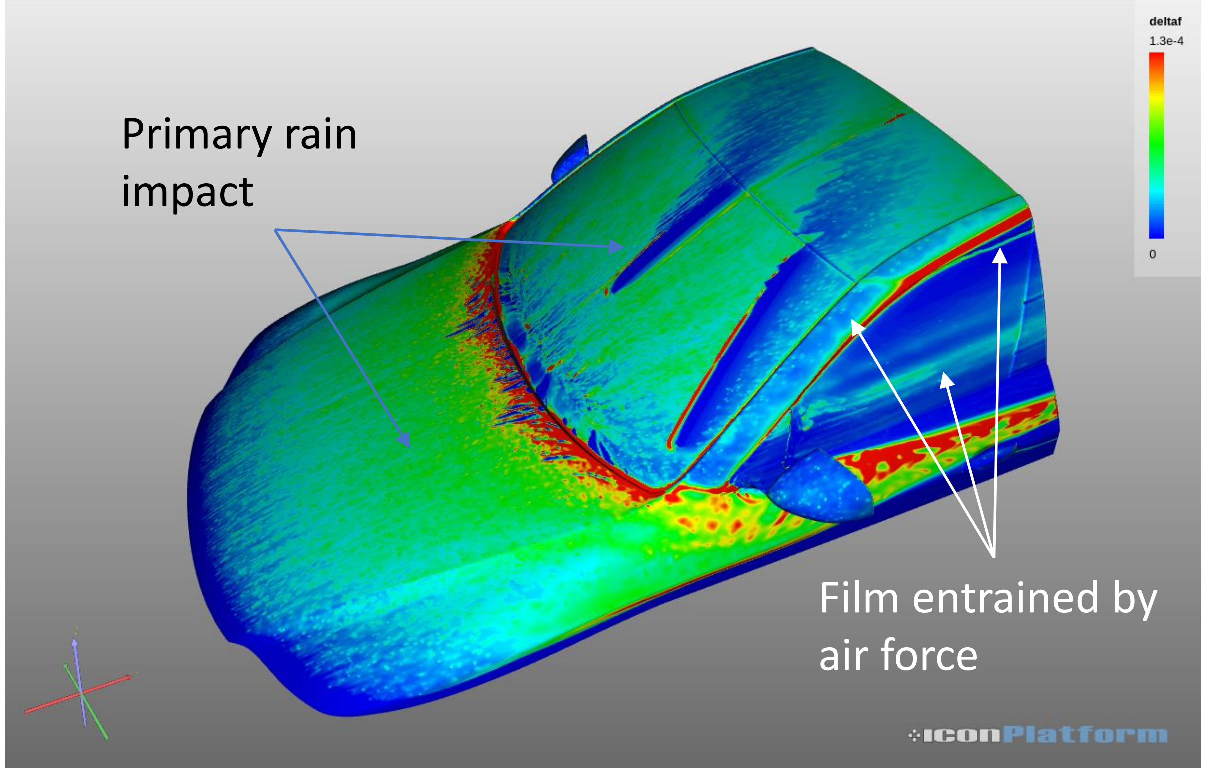


Figure 9. Rain soiling simulation using 1-way coupling

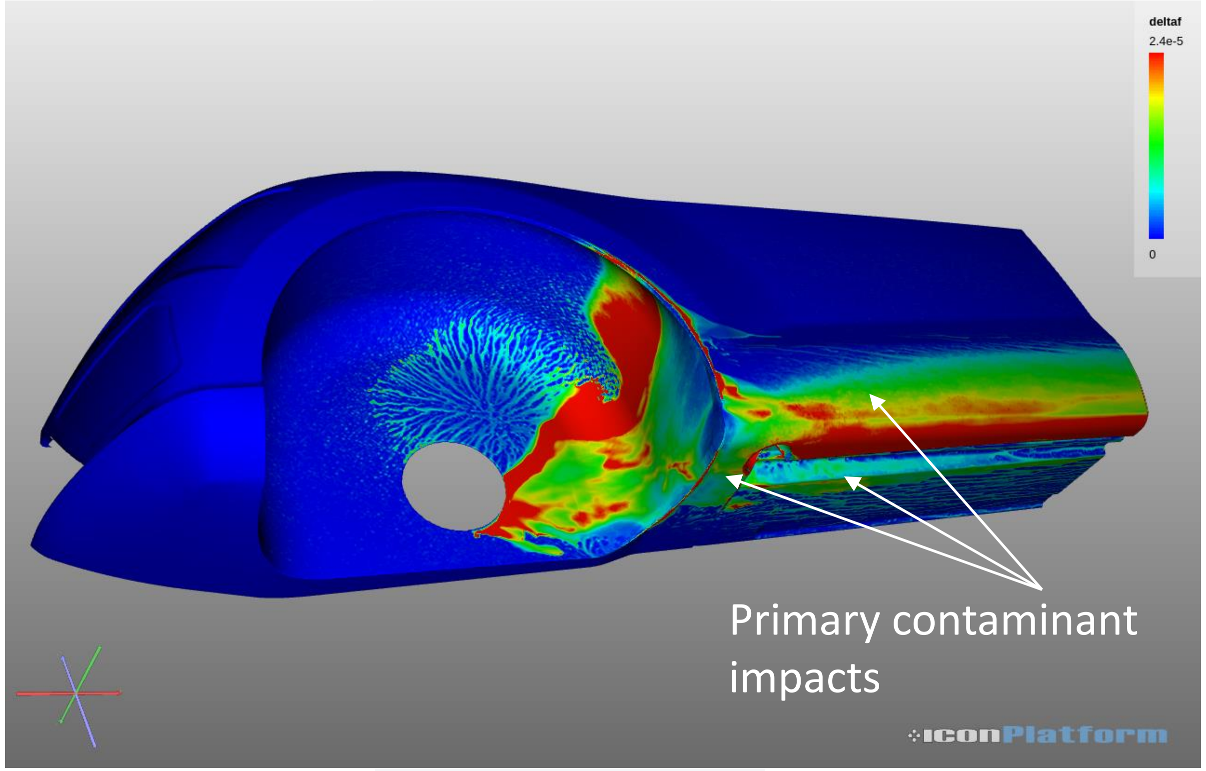


Figure 10. Self-soiling simulation using 2-way coupling

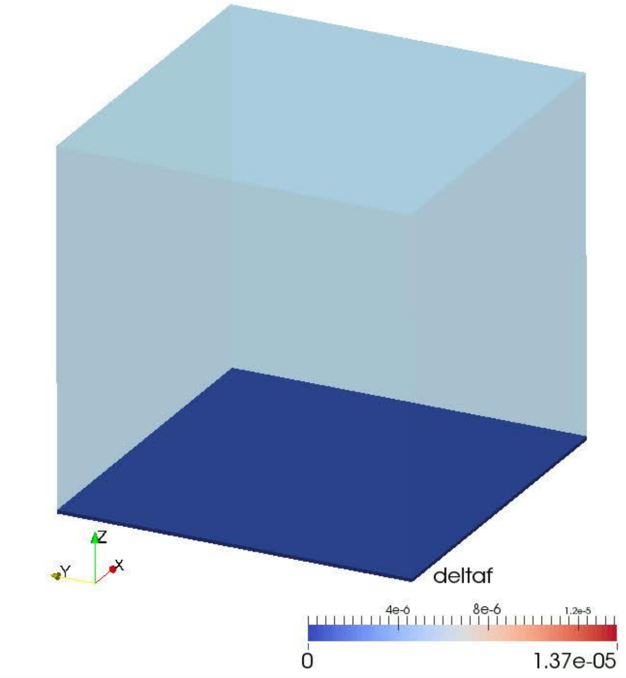
1-way coupling approach is sufficient to analyse the film flow around the A-pillar and the side window

2-way coupling approach is necessary to accurately predict the surface impingement

Vehicle Soiling Methodology

Lagrangian Particle Tracking

- **Key sub-models for accurate particles tracking**
  - Particle dispersion model for 1-way coupling
  - Particle-wall interaction model for splashes on dry walls
  - Particle-film interaction model
    - Splashes on wet walls
    - Film detachment
- **Solver speed-up**
  - Number of primary particles can be several millions
  - Reduction of LPT domain
  - Removal of inactive particles from Lagrangian cloud
  - Special treatment of untrackable particles due to bad grid elements



Animation 3. Particle interaction with wall and film

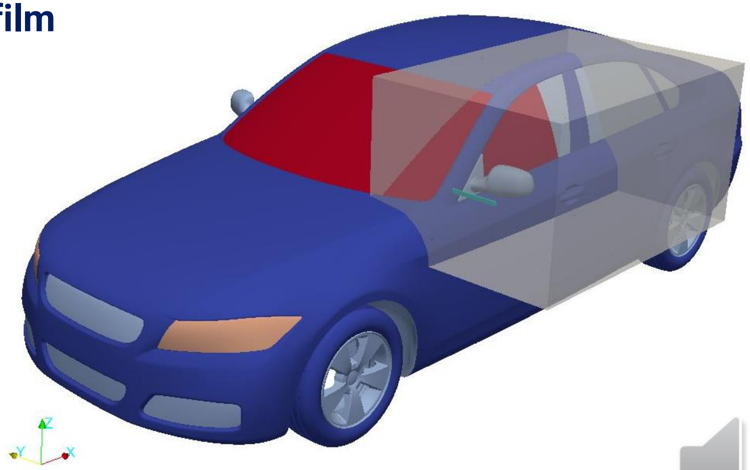


Figure 11. Reduced LPT domain

Vehicle Soiling Methodology
Lagrangian Particle Tracking

- A new particle tracking method called SIMPLEX is now available in iconCFD V5
  - User can switch between SIMPLEX and legacy method for particle tracking
- **New SIMPLEX method**
  - Particle position defined by local coordinates relative to tetrahedra vertices
  - Can be used on any meshes regardless of cell quality
  - Support for moving meshes
- **Advantages over the legacy method**
  - No loss of particles
  - No need for rescue operations
  - As a result, no mesh artefacts in the film solution

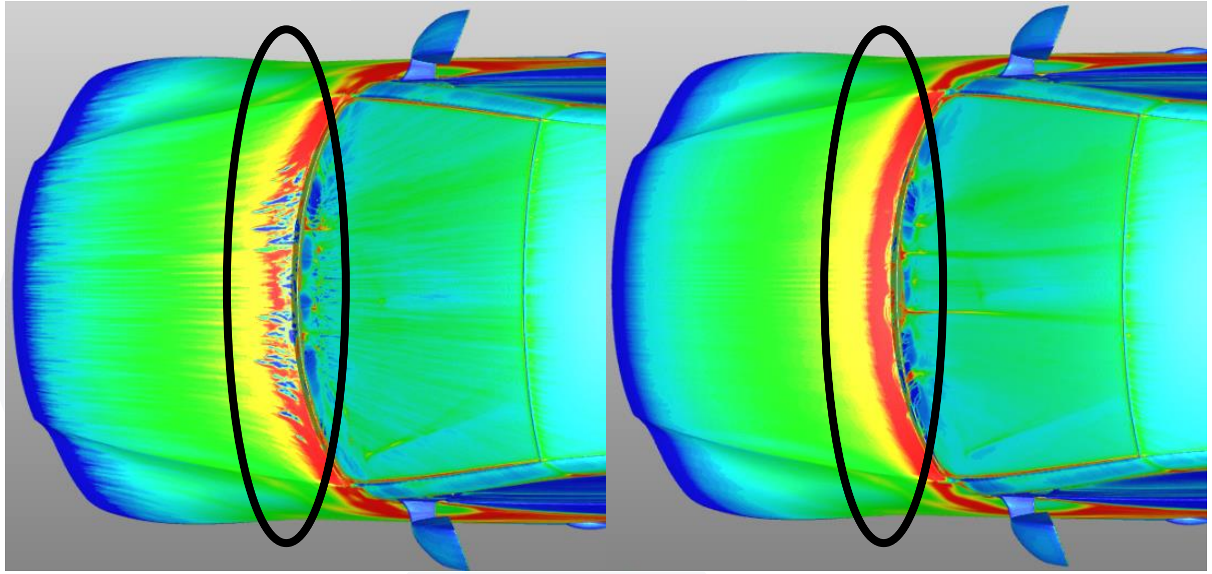


Figure 12. Differences in film solution using the legacy particle tracking method (left) and the SIMPLEX method (right)

Rain Soiling Analysis

Engineering Goals

- Assessment of driver visibility in rainy conditions is part of vehicle safety requirements
  - The rain soiling simulations allow for film flow analysis in areas of interest like the A-pillar, side windows and side mirrors
- For the side windows, the prediction of A-pillar overflow and windshield wiper effects are essential
  - Simulation of film development in these regions can be done with 1-way coupling
  - Good qualitative correlation between numerical and experimental data on industrial cases

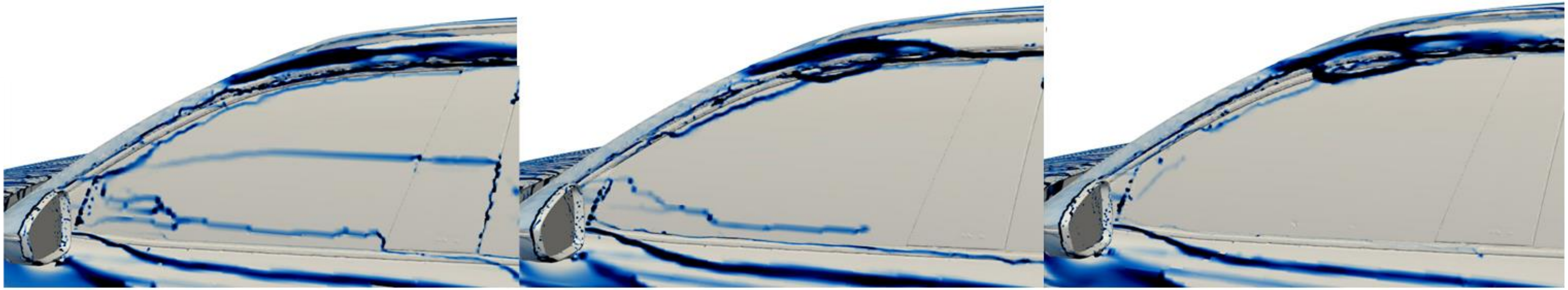


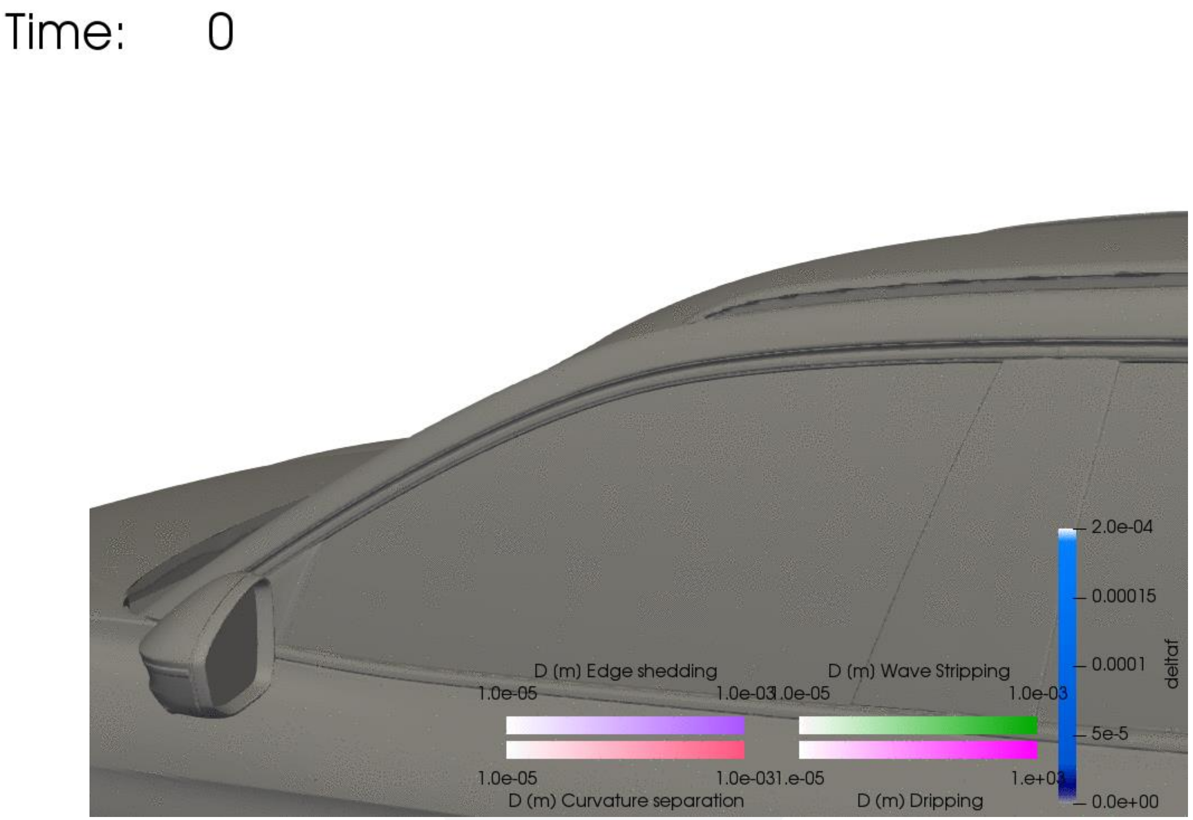
Figure 12. Optimization of side window design for better visibility. Effects of different car door seals on film flow.

Rain Soiling Analysis

Engineering Goals

- Side mirror contamination analysis shows that best level of accuracy is obtained with the 2-way coupling approach
  - Transient mirror wake and A-pillar vortices

- Advanced film re-entrainment models allow to realistically capture secondary rain droplets in the vicinity of the side mirror
  - Impacts on side mirror glass
  - Impacts on side window



Animation 4. Simulation of side mirror contamination with 2-way coupling

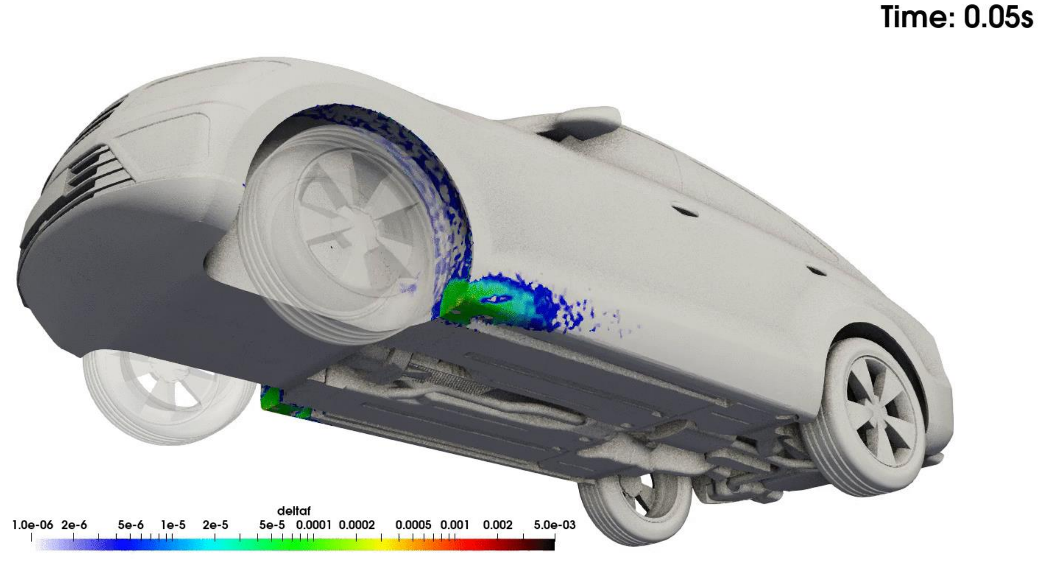
Self-Soiling Analysis

Engineering Goals

- Vehicle self-soiling is caused by the rotation of wheels over substances present on the road (e.g. sand or water)
  - These particles are ejected into the airflow and can hit areas of the car which are critical for the driver's safety and comfort
  - Rear window and sensors contamination
  - Door handle contamination

- Accurate modelling of wheel flow and particles transport is necessary to capture the right contamination patterns
  - 2-way coupling with dynamic mesh around the wheel
  - Fine particles discretisation
  - Realistic particles injection model

Animation 3. Surface contamination caused by wheel rotation



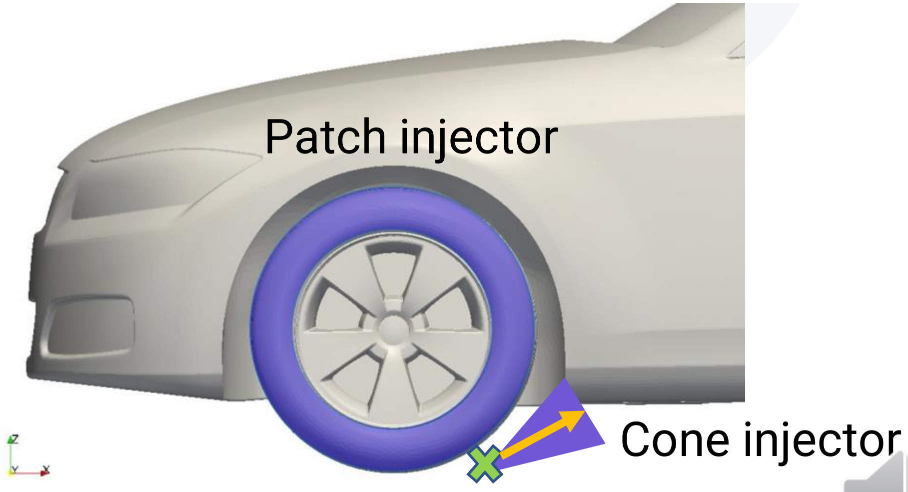


Figure 12. Modelling of wheel injection

Self-Soiling Analysis

Improved Wheel Modelling

- For EA simulations, best accuracy of wheel flow modelling can be obtained with the AMI approach
- Usage of AMI was robust in iconCFD V4 for self-soiling simulations but was computationally prohibitive
- Significant solver speed-up has been achieved in iconCFD V5 making the use of AMI now possible in industrial cases
  - ~11 faster than iconCFD V4 (v4.2.13)
  - Additional 75% speed-up achieved with further optimizations for 2-way coupling simulations

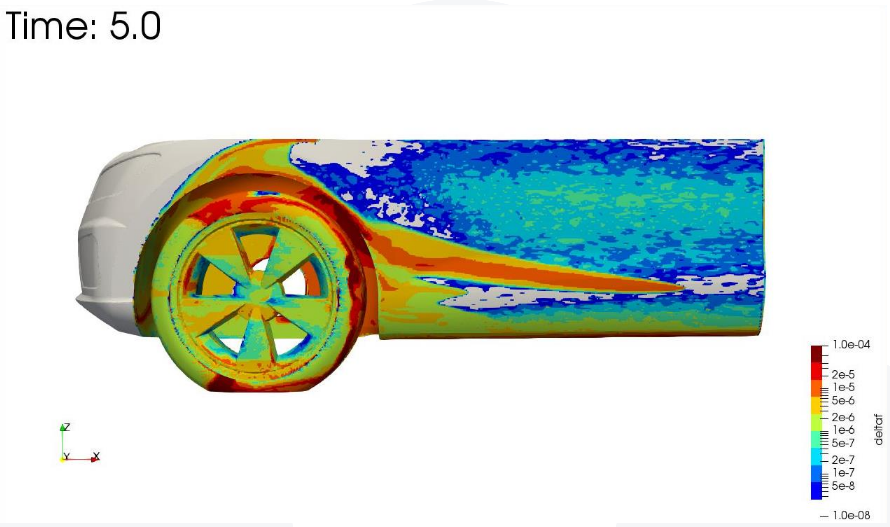


Figure 13. Film solution at 5s for a self-soiling simulation with AMI

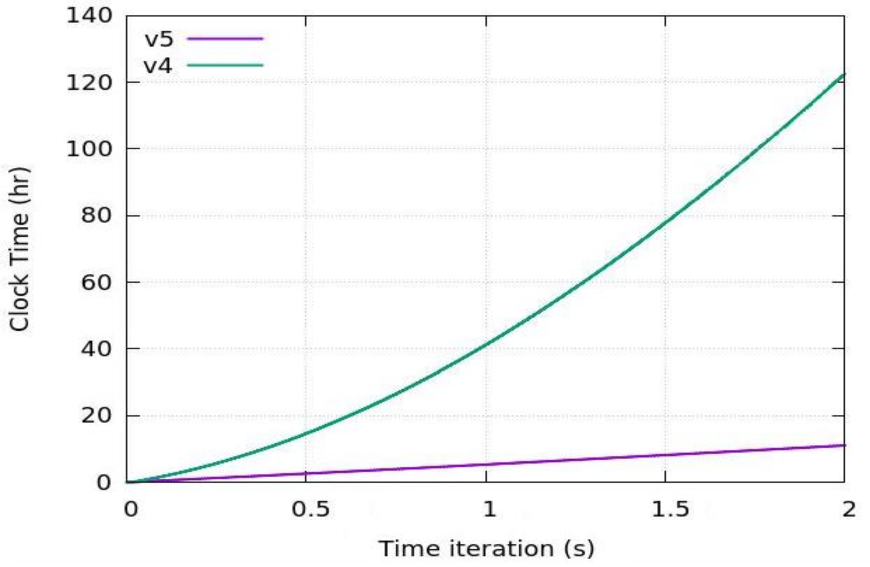


Figure 14. Comparison of solver performance for 2s of flow simulation

Conclusions

Summary

- New enhancements in iconCFD V5 for vehicle soiling methodology has been described
- A new particle tracking algorithm called SIMPLEX which is less dependent on mesh quality has been developed in iconCFD V5
  - There are no loss of particles with this method and no rescue operations are required thereby resulting in no mesh artefacts on film solution
- Rain soiling
  - Industrially validated methodology
  - Fast qualitative design assessment within reasonable runtime even for long physical time (20s)
- Self-soiling
  - Improved solver robustness for fully transient and coupled Euler-DEM-Film simulations
  - Significant performance enhancements have been made for running self-soiling simulations with AMI for rotating wheels
  - Ongoing industrial validation on SUV vehicle type
    - Experimental data of surface contamination on the side and rear parts

Future Developments

Coming soon…

- Modelling of wiper effects on airflow
  - Climatic WT tests as well as on-road tests both show film “pull-back” near the A-pillar
  - It is important to capture the pull-back effect as it affects the film flow over the side window
- Virtual film mesh construction for better surface representation
  - Currently, the film mesh must satisfy specific quality criteria to ensure solver stability
  - Faces that do not satisfy the quality criteria are removed
    - Presence of holes in the film mesh leading to artefacts in the solution
- Film-VOF coupling to capture water accumulation in grooves
  - Currently, film flow over the side window can sometimes be under-estimated

Questions? More Information?

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